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JULY, 1955

COVER PICTURE

The South East Face Passenger Building and the Control Building in the new Central Terminal Area at London Airport, showing part of the extensive outdoor lighting installation at the airport with G.E.C. cut-off fluorescent lanterns.

G.E.C. JOURNAL

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One of the forty North British-G.E.C. electric locomotives supplied to the South African Railways drawing out of Cape Town Station with the Blue Train.

New Short Circuit Testing Station

By W. G. THOMPSON, Ph.D., B.Sc., M.I.E.E. and H. V. WALKER, A.M.I.E.E.
Witton Laboratories.

INTRODUCTION.

THE proper short circuit testing of the types of switchgear used in industry, traction work and for general purposes is of considerable interest to users and manufacturers. Although facilities already exist for carrying out high power tests on alternating current heavy duty switchgear in the G.E.C. High Power Testing Station at Witton which operates within the framework of the Association of Short Circuit Testing Authorities (A.S.T.A.), the Company has always recognised the need for full current and also high power tests to prove on a proper scientific and technical basis the capabilities of apparatus of more modest ratings.

Furthermore, while the heavy duty switchgear testing stations in this country are all alternating current plants, high power testing with direct current is not catered for to the same extent, despite the wide variety of switchgear which is called upon to operate on D.C. systems, particularly in traction and industrial applications.

In this connection, although the amount of direct current power does not in general approach that used with A.C. plants, the increasing size of mercury arc rectifier substations capable of delivering very large fault currents demands test equipment capable of providing short circuit currents of corresponding magnitude.

It follows therefore that a testing station to meet the requirements of the types of switchgear under consideration must be fully equipped to provide both alternating and direct short circuit power.

KINDS OF EQUIPMENT TO BE TESTED.

Some idea of the different kinds of switchgear can be gathered from the fact that the range includes high-speed D.C. circuit breakers for standard traction voltages up to 3,000 volts, substation slow-speed breakers, A.C. and D.C. contactors for traction purposes and industrial use, high rupturing capacity cartridge fuses from the largest to the smallest sizes, a wide variety of switch-fuses and fuse-switches mainly for industrial purposes, distribution equipment for ships, as well as switchgear in the domestic range for hotels, hospitals, shops and private dwellings.

UNDERLYING CONSIDERATIONS FOR TESTING STATIONS.

At present the wide range of equipment which has to be handled is not fully covered by British Standards so that cases arise where customers call for special tests. This means that the testing and recording facilities must be both adequate and sufficiently flexible to meet all reasonable requirements. Great importance is therefore attached to the setting up of representative circuit parameters, the accurate estimation of the prospective fault currents, the accurate metering of the short circuit currents interrupted by the equipment and the proper oscillography of the voltage and current conditions during the tests. In all this work the standards of testing, measurement, recording and presentation have been established over the years by the A.S.T.A. stations and one object of the new station is to provide a corresponding service for the medium powered equipment as comprehensive as that provided for the very large switchgear, but at an installation and operating cost commensurate with the production costs of the gear to be tested.

CORRELATION BETWEEN SERVICE AND TEST CONDITIONS.

The appropriate British Standards determine the conditions of testing for a given piece of equipment. Nevertheless, in considering the requirements of a short circuit testing station, it is desirable to visualise the likely location of the equipment in an electrical network. In this way an appreciation may be gained of the fault currents and circuit conditions likely to be encountered. For example, the typical network representing the large power concentration in a metropolitan area becomes divided into zones of progressively smaller fault currents through successive transformers in the course of stepping down to the lower voltages of the distribution network, though, in the case of large industrial consumers or traction systems, the fault currents can still reach considerable values.

Some indication of the fault currents likely to be encountered in practice for given supply voltages, assuming a typical network in a large load centre, can be seen from fig. 1 which also serves to indicate the combination of voltage and current required to be covered by short circuit testing plant.

A cardinal principle in the design of switchgear is that its normal loading is determined by the rating of the equipment which it serves to protect, taking into account load cycles, diversity factors, etc., while its duty and operation under fault conditions is determined by the fault power of the circuit to which it is connected. Any protective equipment must be capable of clearing a short circuit at its output terminals. It follows there-

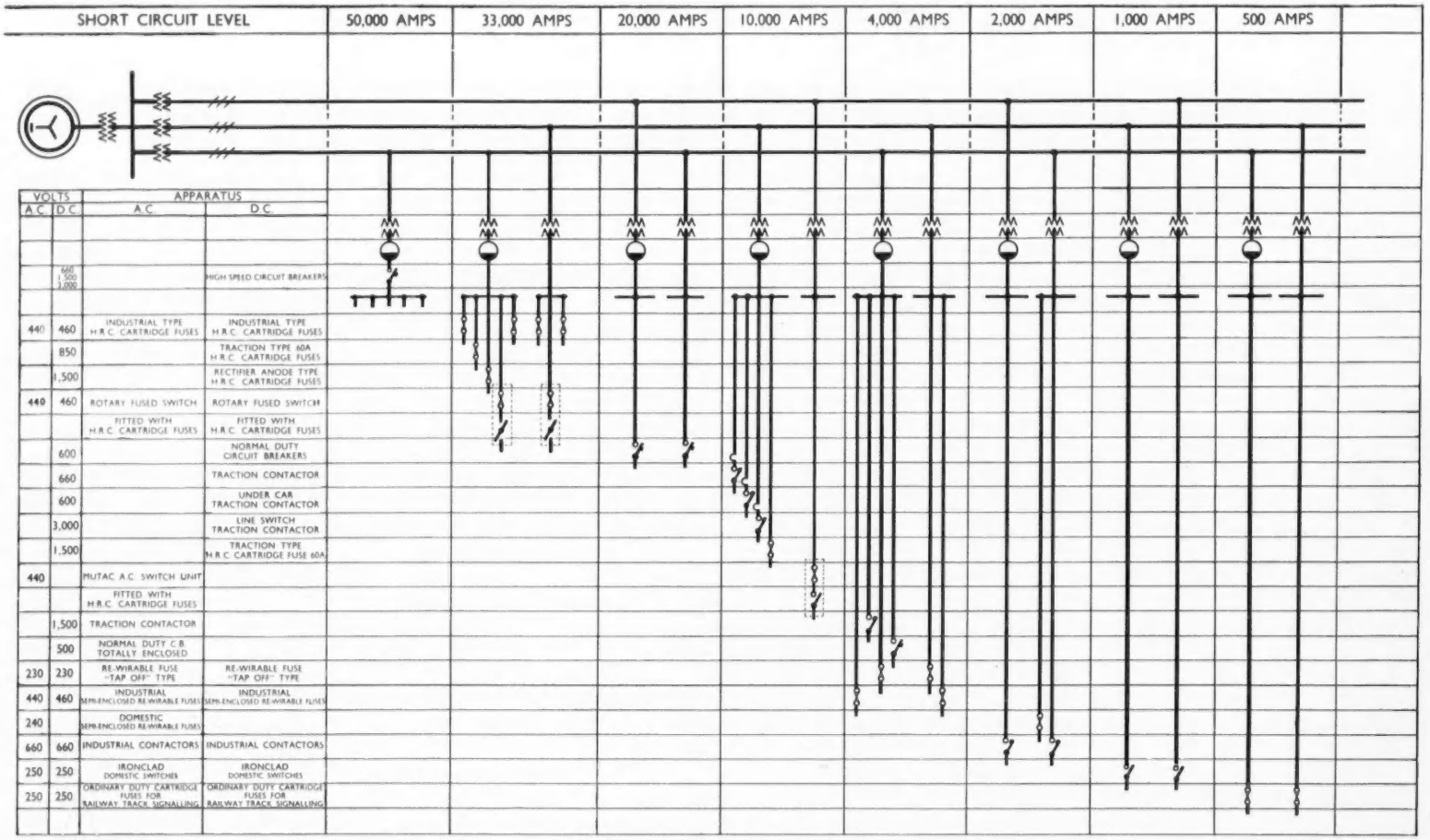

Fig. 1.—Diagram of short circuit levels.

fore that two factors influence the testing requirements for medium power equipment : first, the operating voltage which must correspond to any of the standards in common use on distribution systems, and second, the test current which must be at least equal to the fault current encountered in practice, as determined by the installed kVA and circuit impedance on the supply side.

Although it is not possible to lay down hard and fast limits, some indication can be given of the maximum short circuit current likely to be encountered in service for any given standard supply voltage. Manufacturing policy will require each standard voltage to be covered by a number of different kinds and sizes of equipment, each with its appropriate rating and breaking capacity. It is important to note that the equipment must be proved to function properly at any value of fault current within its specified rating and at the same time be capable of interrupting currents in the ordinary working range, including the magnetising current of transformers on no load.

In the operation of switchgear the opening of the circuit produces an arc discharge and suitable conditions have to be set up in the device to prevent the formation, or bring about the certain extinction, of the arc. The co-existence of the after-effects of arcing, particularly heating in the arc path, with the recovery voltage of the circuit, greatly adds to the severity of the duty on the device. Therefore, the power factor in A.C. circuits, and the time constant in D.C. circuits, are important parameters which must be properly considered in designing the test equipment.

REQUIREMENTS OF THE TEST PLANT.

A.C. Testing.

It will be seen from fig. 1 that the test equipment has to be sufficiently adaptable in design to cope with a wide range of equipment whose operating characteristics may differ considerably although in every case the final criterion is that of effective arc extinction. The principal differences between the equipments to be tested are the media in which arc extinction takes place and whether, for absolute safety, the apparatus has to extinguish the arc in the first half-cycle of operation, as, for example, in most types of fuses, or whether arcing can be permitted to persist for a few half-cycles before the interruption is completed, as in the case of contactors or many types of circuit breaker. When arcing must be limited to a half-cycle the test plant must permit, if required, the prospective short circuit current to have a high degree of asymmetry. In other cases the test plant must be capable of maintaining steady fault current during the arcing period.

This means that the test plant has to provide for alternating currents of the order of 15,000 amps. and voltages up to 1,700 volts A.C.; to have circuit

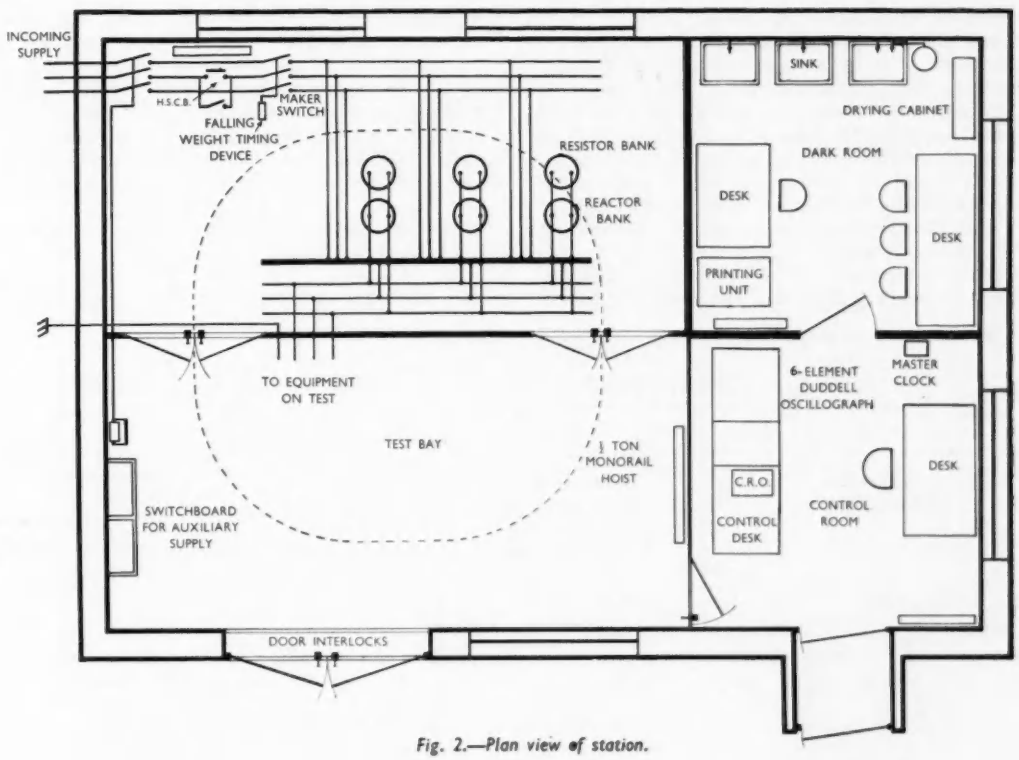

Fig. 2.—Plan view of station.

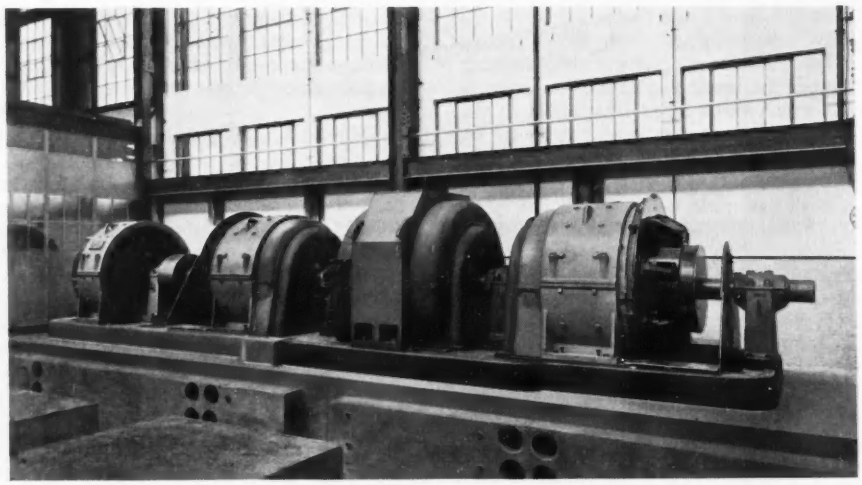

Fig. 3.—Motor-generator sets during installation.

components which will enable tests to be made at high or low power factors at different frequencies and recovery voltages, and above all to have sufficient stored energy to inflict the proper severity upon the equipment under test.

D.C. TESTING.

Similar considerations apply to D.C. testing. These again will depend upon the source of direct current which may range from very large mercury arc rectifier installations, as used in electrolytic plants, or large generators in industrial plants, to small power units. The plant must therefore be able to deliver adequate power at any operating voltage up to 4,000 volts D.C., and short circuit currents up to 40,000 amps., and include means of arranging the testing circuit to have suitable characteristics such as the time constant and form of recovery voltage.

Two other points should be mentioned: first, the fact that much of the apparatus for which the station is intended may have to be used either on A.C. or D.C. circuits without alteration in design, and second, in some cases the apparatus may have to function in rectifier or other circuits wherein a combination of A.C. and D.C. fault conditions may be experienced.

Finally, the usual alternative arrangements for short circuit testing must be embodied in the plant to render it possible to apply predetermined short circuit values to equipment already in circuit, to enable equipment to be closed on to a short circuit, i.e. break and/or make-break tests and also to permit reclosure of a piece of equipment a number of times before locking out under a fault. The essential requirement in all such cases is to be able to apply the short circuit under controlled and predetermined conditions.

CONSIDERATIONS OF TYPES OF TEST PLANT FOR MEDIUM POWERS.

Where both A.C. and D.C. testing are envisaged both static and rotating plant come under considera-

TABLE 1(a).

DIRECT CURRENT CIRCUIT PARAMETERS.

Arrangement of generators	Volts	Maximum short circuit current					
		Dead short circuit		With maximum test inductive load		With maximum test resistance load	
		Amp.	Time constant	Amp.	Time constant	Amp.	Time constant
4 in parallel	460	40,000	0·017	3,500	0·138	38	0·0000166
4 in parallel	1,000	40,000	0·0066	7,600	0·138	83	0·0000125
4 in series/parallel	2,000	20,000	0·0066	12,000	0·112	166	0·00005
4 in series	4,000	10,000	0·006	10,000	0·051	333	0·0002

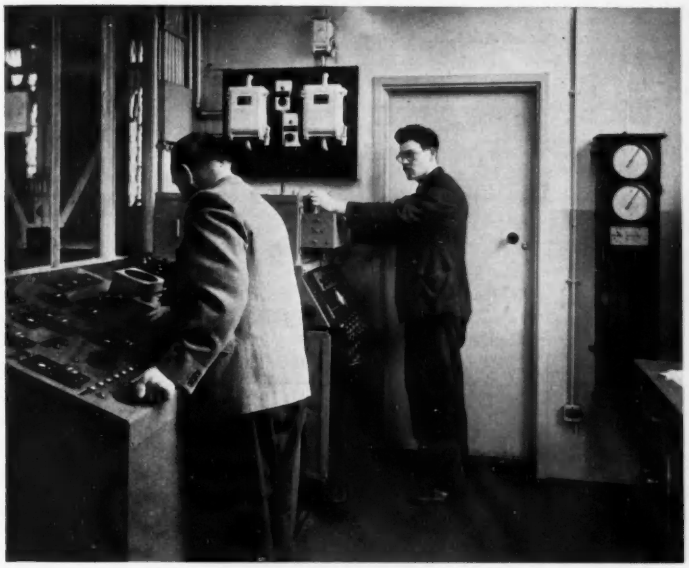

Fig. 4.—Control room.

tion ; the static plant being transformers for A.C. testing and mercury arc rectifier equipment for D.C. testing, while both A.C. and D.C. testing can be carried out with suitably arranged motor generator sets.

The use of transformers involves three main problems, first that of providing an adjustable output voltage. This means supplying the transformers through an induction regulator or through a regulating transformer of the variable ratio type either continuously variable or by providing a large number of tappings on the windings of the transformer.

Second, there is the influence of the supply voltage and frequency variations upon the accuracy and consistency of the test results and the limitation of testing to a frequency of 50 cycles per second.

Third, the absence of any form of stored energy in the test plant means that the effects of heavy short circuits might be disturbing to the voltage regulators in other areas of the works.

These objections apply equally to the case of a mercury arc rectifier equipment for D.C. testing with the additional drawback of the presence of power factor and ripple voltage effects if voltage adjustment by grid control were adopted. On the other hand there is the possibility of initiating the test by unblocking the control grids of the rectifier and conversely using arc suppression to give high-speed protection in the event of the apparatus under test failing to function properly.

In both A.C. and D.C. testing with static equipment for variable voltage the amount of reactance in the circuit and the maintenance of equipment subject to repeated short circuits come into consideration.

Rotating plant on the other hand in the form of a D.C. driven D.C./A.C. motor generator set provides flywheel stored energy, independence from mains fluctuation, the advantage of a wide frequency range, a wide voltage range and ease of control by means of the

TABLE 1(b).

ALTERNATING CURRENT CIRCUIT PARAMETERS.

Arrangement of generators and windings	Volts	Maximum short circuit current					
		Dead short circuit		With maximum test inductive load		With maximum test resistance load	
		Amp.	P.F.	Amp.	P.F.	Amp.	P.F.
1 Alternator in parallel (star)	880	10,000	0·15	263	0·0247	127	0·99
2 Alternators in parallel in parallel/star ...	880	13,600	0·15	264	0·0247	127	0·99
1 Alternator in parallel/delta	500	8,650	0·15	153	0·0212	72	0·99
2 Alternators in parallel in parallel/delta ...	500	11,700	0·15	153	0·0212	72	0·99
1 Alternator in series/star	1,760	10,850	0·15	514	0·0202	253	0·99
2 Alternators in parallel in series/star ...	1,760	14,750	0·15	520	0·026	253	0·99
1 Alternator in series/delta	1,000	8,500	0·15	306	0·0212	144	0·99
2 Alternators in parallel in series/delta ...	1,000	11,500	0·15	306	0·0212	144	0·99

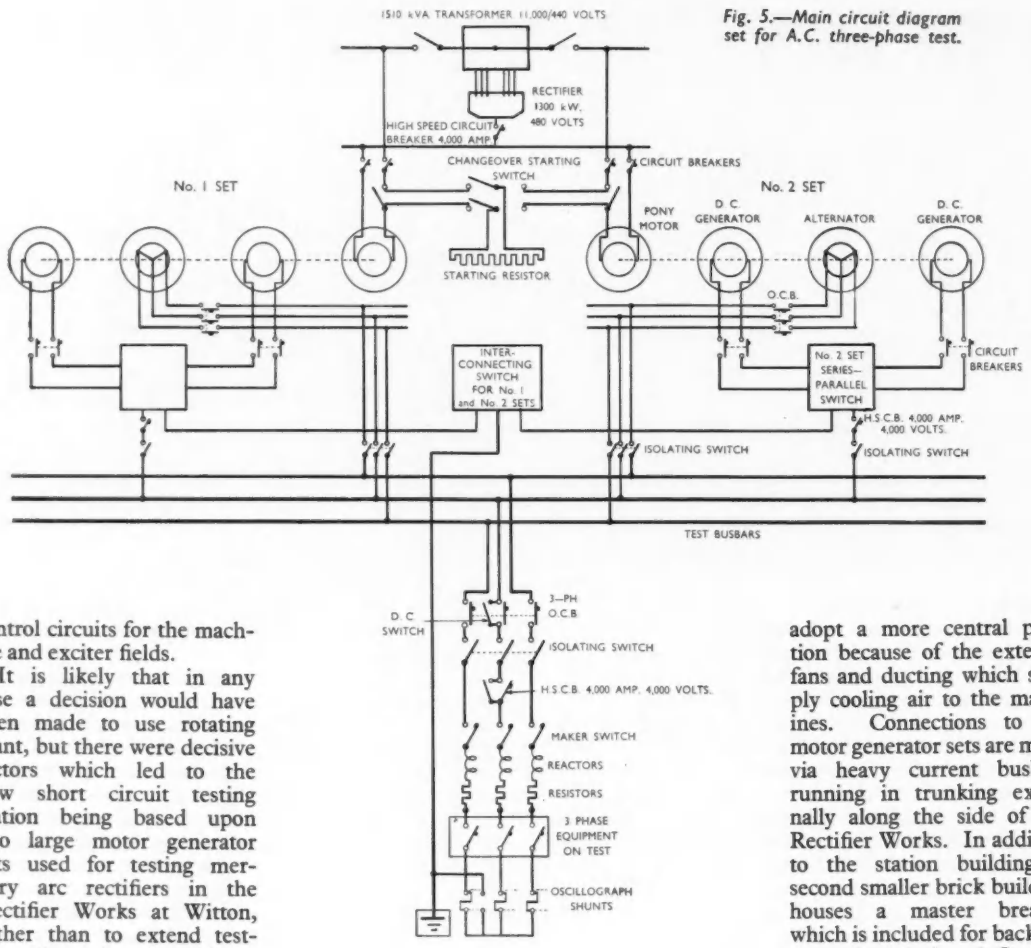

Fig. 5.—Main circuit diagram set for A.C. three-phase test.

control circuits for the machine and exciter fields.

It is likely that in any case a decision would have been made to use rotating plant, but there were decisive factors which led to the new short circuit testing station being based upon two large motor generator sets used for testing mercury arc rectifiers in the Rectifier Works at Witton, rather than to extend testing plant in the Witton Laboratories, and this decision led to facilities being made available far beyond what might have been considered economically justified in setting up a station of the kind devoted solely to the testing of medium powered apparatus. Briefly the reasons were the ground available for building and extending the station, the fact that the same machines had already been used for similar tests, the ease with which both power and control circuits could be arranged, the advantages already stated above for rotating plant and the improvements in the load factor of relatively costly test plant by the dual purpose for which it could be used.

DESCRIPTION OF THE TESTING STATION.

(a) General Layout.

The general layout of the testing station is shown in plan view in fig. 2. The station was built as close as was possible to the motor generator sets, being situated near one end of the two sets, which are themselves in line, and at right angles to them. It was not possible to adopt a more central position because of the external fans and ducting which supply cooling air to the machines. Connections to the motor generator sets are made via heavy current busbars running in trunking externally along the side of the Rectifier Works. In addition to the station building, a second smaller brick building houses a master breaker which is included for back-up protection during A.C. testing, while a third small concrete building provides storage space for components or equipment which is either awaiting, or has completed, its tests.

The station building itself is subdivided into four parts, namely the test bay proper, a switching bay containing links and components for setting up the test circuit constants, an observation and instrumentation room housing the control desks and lastly a combined photographic room and office, thermostatically controlled for temperature, for developing and printing the oscillographic and any other photographic records. Provision was made in the design of the building for the later addition of a second storey, and access to the site is by means of an external roadway leading to double doors in the test bay which are capable of taking the largest piece of equipment likely to be tested. The test and switching bays are serviced by an overhead $\frac{1}{2}$-ton monorail crane to facilitate the handling of apparatus. The building has windows on three sides to give adequate lighting by day ; it is equipped

with fluorescent lighting throughout and also with proper heating facilities.

(*b*) MOTOR-GENERATOR PLANT AND ITS CONTROL.

Fig. 3 shows the motor-generator sets during installation. Briefly, each of the sets, which are practically identical, consists of four machines all connected on a common shaft system. There are a 750 h.p. D.C. driving motor, a 3,000 kVA 3-phase alternator and two separately excited 1,500 kW D.C. machines. The driving motors for both sets are started from a common starting panel which, by means of a double pole changeover switch, serves either one or other of the sets during the running up period so that they can be started independently at any time. Furthermore, each set forms a complete unit with its own switchgear and metering system.

As regards the individual machines, the D.C. driving motors are capable of stable operation over a wide range of speed and load ; this provides for a correspondingly wide frequency range for the salient pole alternators which are excited from independent small motor-generator sets. Subdivision of the alternator windings permits the setting up of various star and delta arrangements, the series star connection providing 1,760 volts at 750 r.p.m.

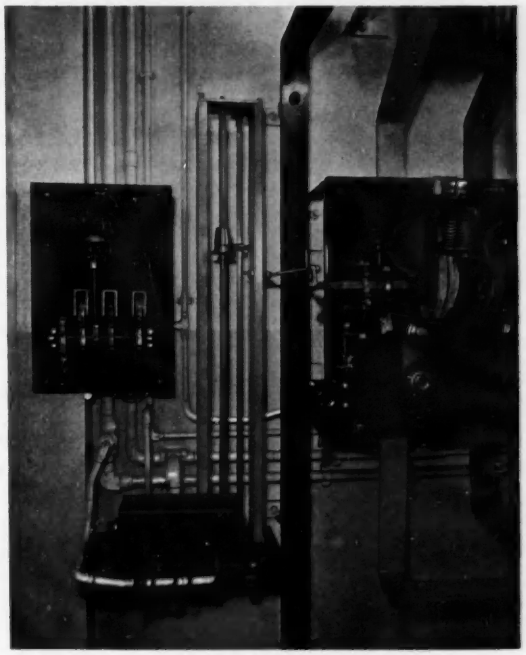

Fig. 7.—Falling weight and rotary relay mechanism.

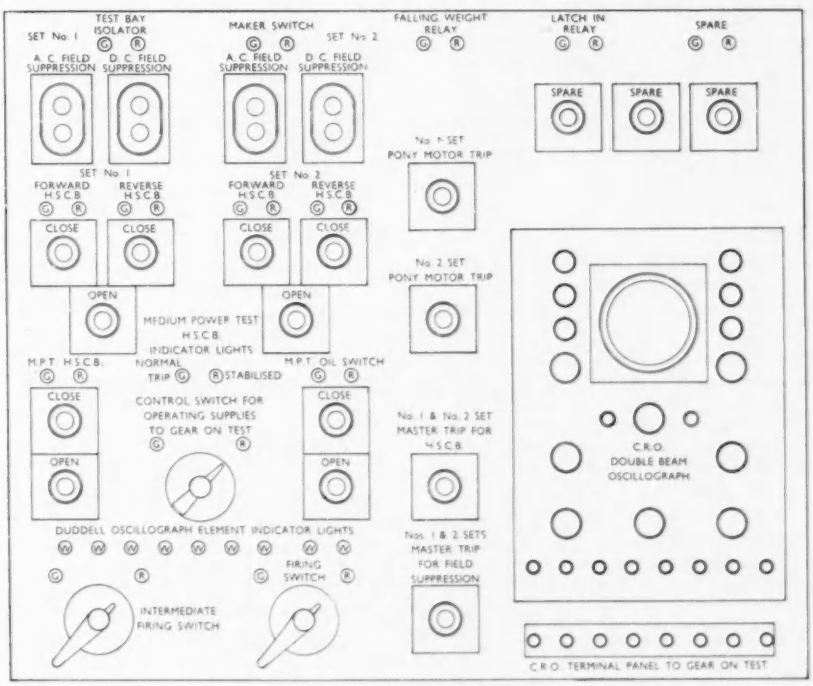

Fig. 6.—Control room desk layout.

The fully compensated 1,500 kW D.C. machines capable of 1,000 volts per machine are separately excited by a supply from the mercury arc rectifier which supplies the driving motors.

It will be appreciated that the numerous possible combinations of the respective A.C. and D.C. machines provide the ideal flexibility in setting up testing circuits with different voltages and current characteristics for short circuit tests.

The various arrangements used, together with the short circuit characteristics, etc., are shown in Table 1 and it might be mentioned that the insulation of one of the sets is arranged to permit operation at 4,000 volts above earth.

SWITCHING ARRANGEMENTS.

Fig. 5 shows the main circuit diagram from which the runs of the circuit can be traced from the machine to the test circuit. The switching arrangements fall naturally into four sections: (*a*) for setting up circuits; (*b*) protecting the machine circuits; (*c*) protecting and making connections at the station and (*d*) control gear.

The equipment for setting up the circuits and arrangements indicated in Table 1 is arranged as permanent gear consisting mainly of heavy busbar sections with changeover links and isolators. For protection the outputs of both D.C. and A.C. machines of the two motor-generator sets are connected to a main switchboard incorporating oil circuit breakers, while each of the four D.C. machines has its own D.C. circuit breaker.

The power for short circuit testing is transmitted from the machines to the testing station by an overhead busbar system consisting of three sets of 4 in. $\times \frac{1}{4}$ in. copper busbars, the middle set being used for either A.C. or D.C. testing. The busbars enter the master oil switch house, and means of isolating for safety and maintenance are incorporated as well as by-pass arrangements to prevent a heavy current D.C. arc

G.E.C.

WITTON LABORATORIES

MEDIUM POWER A.C./D.C. TEST RESULT OF TESTS

W.L.Z. No. 4442 W.L. No. 9018 Works Order No. M.P.T. Programme No. 30 M.P.T. SUBJECT No. 101 Date 23/4/54

TEST ITEM High breaking capacity cartridge fuses. Type T. Rating 60 amps 660 volts.

OBJECT OF TEST D.C. breaking tests at 660 volts under circuit conditions complying with D.C.4 of B.S.88:1952

	Modification Number	None		None		None		None		None		None							
	Series of Operations	B		B		B		B		B		B							
	Phase																		
	Test Number	1709A		1709B		1709C		1711A		1711B		1711C							
	Duddell Osc. Number	1422A		1422B		1422C		1424A		1424B		1424C							
	Cathode Ray Osc. Number	56A		56B		56C		57A		57B		57C							
	Prospective Current Osc. Number	1421A		1421A		1421A		1423A		1423A		1423A							
	Inductance M.H.	0.36		0.36		0.36		7.05		7.05		7.05							
	Time Constant Power Factor	0.018		0.018		0.018		0.017		0.017		0.017							
Current	Prospective Current	33,200		33,200		33,200		1580		1580		1580							
	Cut-Off Current	3500		3850		3850		950		950		975							
	Maximum D.C./Peak A.C. Current Broken																		
	Peak Current																		
		DUDDELL	C.R.O.	DUDDELL	C.R.O.	DUDDELL	C.R.O.	DUDDELL	C.R.O.	DUDDELL	C.R.O.	DUDDELL	C.R.O.	DUDDELL	C.R.O.	DUDDELL	C.R.O.	DUDDELL	C.R.O.
Volts	Applied Voltage	660		660		660		667		660		667							
	Point on Voltage Wave—Making	55°		50°		60°		40°		55°		50°							
	Point on Voltage Wave—Breaking																		
	Peak Arc Voltage	964	1100	1222	1222	1150	1280	960	1150	1200	1284	1070	1120						
	Peak Arc Voltage																		
	Peak Arc Voltage																		
	Restriking Voltage	910		925		786		724		720		777							
	Recovery Voltage	647		642		647		624		624		652							
	Average Recovery Voltage																		
M.V.A.	M.V.A. Broken Per Phase																		
	Total M.V.A. Broken																		
Watts	Arc Energy M.W. Peak Watts-Hours	2.10		2.50		2.40		1.10		1.35		1.20							
Time	Pre-Arcing Time—Milli-seconds	1.71		1.86		1.73		15.2		15.8		15.6							
	Arcing Time—Milli-seconds	2.91		1.95		2.76		20.7		19.8		18.3							
	Total Time—Milli-seconds	4.62		3.81		4.49		35.9		35.6		33.9							
Data	Volts to Frame/Case																		
	Resistance of Fuse Link before Test Ohms	0.0026		0.0025		0.0026		0.0025		0.0025		0.0025							
	Insulation Resistance before Test																		
	Condition of Apparatus after Test																		
	Earth Fuse																		
	Resistance of Fuse Link after Test Megohms	50		50		50		50		50		50							
	Insulation Resistance after Test Megohms	50		50		50		50		50		50							
	Fuse Carrier			Undamaged						Undamaged									
	Fuse Base			Undamaged						Undamaged									
	Fuse Carrier Contacts			Good condition						Good condition									
	Fuse Base Contacts			Good condition						Good condition									
	Fuse Body	Intact		Intact		Intact		Intact		Intact		Intact							
	End Caps	Intact		Intact		Intact		Intact		Intact		Intact							
	Amount of Wire Fused	70%		65%		65%		70%		70%		70%							
	Amount of Sand Fused	10%		15%		15%		10%		10%		10%							
Results	Results and Observations on Test	Test A.B.C. Fuse Nos. 1.6.7. Fuses cleared the circuit correctly. Indicator operated on all fuses						Test A.B.C. Fuse Nos. 13,14,15 Fuses cleared the circuit correctly. Indicator operated on all fuses.											

NUMBER OF POLES: 1

NUMBER OF BREAKS/POLE:

Note 1
Volts maintained across each fuse for 30 seconds after the short-circuit.

Note 2
Test No. 1711 A.B.C. carried out to comply with clause 24b of B.S.88:1952 when the value of cut-off current in the test at 33,000 amps. does not reach 60% of this prospective current value.

TESTING ENGINEER: E.C. Hardy

RECORDING ENGINEER: D. Evans

SIGNED: A.H. Walker

Fig. 8.—Test data sheet.

being produced on the master oil switch. D.C. protection of the test supplies is provided by a local high-speed D.C. circuit breaker.

The various components, i.e. resistance banks, reactors, etc., which determine the characteristics of the circuit are housed in a screened bay adjoining the test enclosure and a comprehensive link system is incorporated to give any desired series or parallel arrangements. This provides for complete flexibility and covers the wide range of current and voltage settings required in the testing of the many different kinds of equipment.

The parameters according to the different settings are shown in Table 1. The test circuit terminates in the test bay proper in an insulated panel mounting the necessary instrumentation and oscillograph shunts to which the apparatus under test is connected by heavy cables.

THE CONTROL ROOM.

The control room (fig. 4) is the nerve centre from which the whole of the testing is controlled and provides direct observation of the equipment under test by the operator from the control desk. In view of the small physical size of some of the equipment to be tested the observation point is made as close to the testing position as safety reasonably permits. The top of the control desk, fig. 6, is an inclined panel with all necessary controls to hand for carrying out the making sequence of switching, operating auxiliary supplies for actuating equipment under test, initiating the short circuit and a master controller for shutting down the whole plant in an emergency.

The control desk incorporates a cathode ray oscillograph for recording transient phenomena ; a six-element Duddell oscillograph fully equipped with instruments, synchronised clocks and so forth, together with recording cameras, is mounted alongside the desk.

The photographic darkroom, fully equipped for carrying out rapid developing and printing of the oscillograph or other photographic records, also adjoins the control room and provides additional office space when not in use as a darkroom.

INSTRUMENTATION AND RECORDING.

Accuracy of instrumentation, recording and metering is of paramount importance in all forms of electrical testing. This is particularly so in short circuit testing, where abnormal and transitory conditions exist during the measurements of circuits of several thousands of amperes over periods totalling only a few milliseconds.

The proper carrying out of the tests entails the simultaneous measurement and recording of current, voltage, and power and often mechanical movement in such a manner that instantaneous values can be accurately determined and correctly correlated on a time basis. This is achieved by the six-element Duddell oscillograph, one of the oscillograph elements being of the wattmeter type for the measurement of instantaneous power. Special features of this oscillograph are intensification of illumination during exposure, an adjustable-speed driven camera-drum having a double motor drive giving wide speed ranges at fast and slow speeds and a tachometer to enable speed to be adjusted to suit the timing of a falling weight mechanism (fig. 7) which controls the duration of the short circuits.

OPERATION AND SAFETY.

During the process of applying a short circuit the operation of the station is under the control of the falling weight mechanism and a rotary relay. The falling weight arranges the time intervals between successive stages of a testing operation and, finally, by releasing the catch of the rotary relay, terminates the duration of the short circuit currents, if this has not already been done through the successful operation of the equipment under test.

The falling weight is released by a catch mechanism rigidly coupled to, and actuated by, the " maker " contactor ; the distance through which the weight falls before releasing the catch of the rotary relay can be adjusted to vary the duration of the short circuit. At its lowest time setting the weight still possesses sufficient stored energy to ensure that, in the event of failure of the spring controlling the opening of the rotary relay, the operation of the relay is completed and the protective system remains effective.

The rotary relay controls the operation of the master circuit breakers, the field suppression systems of the motor-generator sets and closes the shutter mechanism of the Duddell oscillograph at the end of the short circuit period.

The combined mechanism of the falling weight and rotary relay enables the interval over which the short circuit can be controlled to be adjusted between 4 and 25 cycles of a 50 cycle supply. Manual control is used when it becomes necessary to apply the short circuit for more than 0·5 sec. In these circumstances the maximum permissible value of the short circuit current is lower because of the risk of overheating the machines, and the plant protection is therefore set for the normal overload tripping so that, if a heavy short does develop, the equipment and plant are still completely protected.

SAFETY.

The two main principles governing the design of the station were the safety of the testing staff and the protection of the test plant. The former has been achieved by providing complete mechanical protection by expanded metal and glass screens at the control desk, and by preventing access to the test bay and test plant whenever the main generator circuits are alive. Automatic cutout interlocks on all the doors leading to the bays operate to open the master circuit breakers and render the main circuit dead. To prevent the main generator voltage penetrating any circuits in the control room, auxiliary A.C. contactors, with special insulation features and supplied from an isolating transformer,

are used to operate the master circuit breakers and oscillograph mechanisms as well as the aforementioned timing gear for carrying out short circuits to a prearranged plan.

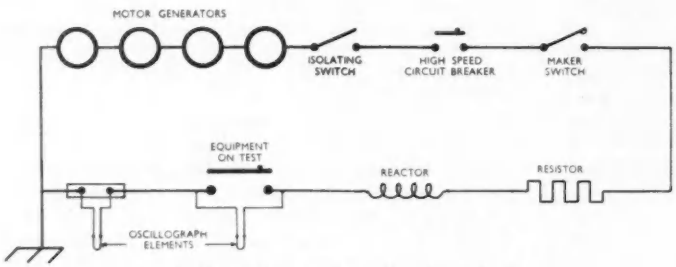

Fig. 9.—Schematic circuit diagram for D.C. tests.

Protection of the test plant is provided by a comprehensive system of electrical safety measures embodying earth leakage on the main circuits and on the field systems, overcurrent protection, and arrangements for field suppression of both A.C. and D.C. generators. Finally, a hand-operated master switch enables the whole plant to be made ' dead ' in an emergency.

SPECIFICATION OF TEST AND PRESENTATION OF RESULTS.

The effectiveness of a short circuit testing station does not rest solely on the efficient operation of the test plant, nor is it intended to be self-sufficient in the sense of retaining the information acquired in the discharge of its work. Broadly speaking, its work falls into three main categories : first, definite tests on given items of equipment to determine their performance with respect to a specification ; second, progressive series of tests providing proving data for ranges of equipment in course of development ; third, applied research in the form of investigating fundamental phenomena manifested in the operation of equipment and of general interest to designers. The effective working of the station will therefore depend upon the correct and precise specification of the tests to be carried out, their efficient execution in which all essential data are accurately measured and recorded with the maximum economy of time and effort and, finally, the presentation of data in proper form with the minimum of delay.

In view of the wide variety of equipment which the station is called upon to test, requirements often differ considerably from one test to the next. Experience has shown the need for reasonable precision in specifying the tests, and the operating staff is encouraged to challenge any request which appears in too general a form. Although the full British Standard tests are inevitably applied to a new form of apparatus in final stages of development, both clarity of thought and economy of effort result from restricting tests to their immediate objective.

Similarly, in the presentation of test data and information it has been found advantageous to have standard comprehensive data sheets which have been specially designed to suit the many types of equipment tested and the particular test circuit conditions used. The main benefits are that a complete presentation of results is obtained and essential data are not overlooked, as might be the case if a different presentation had to be thought out for each class of gear. Fig 8 shows a typical form of data sheet used for tests on fuses.

SOME TYPICAL EXAMPLES OF TESTS ON EQUIPMENT.

Fig. 9 shows the basic circuit with the test plant set up for a test on a 3,300 volt, 300 amp D.C. circuit breaker of the traction type, illustrated in fig. 10. A typical oscillogram taken during a test is shown in fig. 11. In the test, the breaker is shown successfully interrupting a short circuit current of 4,000 amps. at 3,300 volts in 0·41 sec.

An example of a three-phase test on a switch-fuse, in which reactance is included in circuit (fig. 5) to cause operation at a power factor of 0·2 lagging, is shown in fig. 12. It will be seen that the short circuit current of 8,000 amp peak asymmetric at 440 volts was fully interrupted in 0·5 cycle.

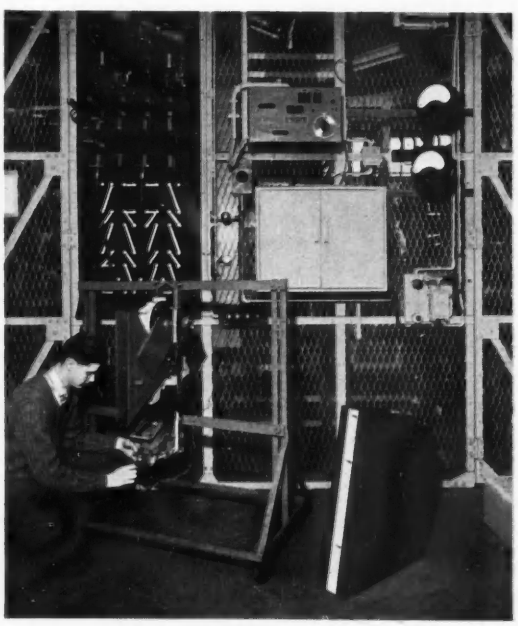

Fig. 10.—D.C. traction line breaker.

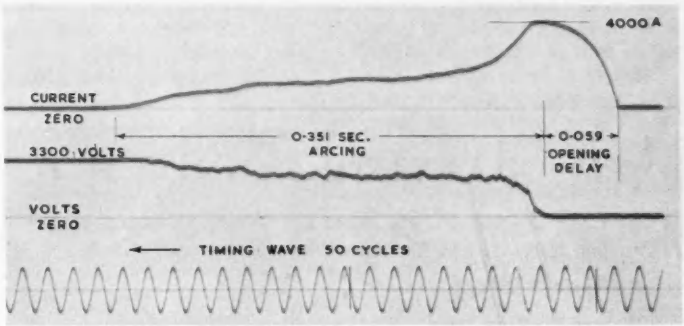

Fig. 11.—Oscillogram of D.C. test on a traction line breaker.

CONCLUSIONS.

The provision of a fully equipped testing station to cater for the medium power range of switchgear, which supersedes earlier *ad hoc* methods of testing on available motor generators, has proved of inestimable value in expediting the improvement of existing types of switchgear and the development of new types. Not only have the standards of testing and the presentation of results been welcomed by everyone concerned in these investigations, but the economy, speed and safety with which the work can be carried out, as a result of the permanent installation of test gear, have completely justified the expense of constructing and operating the station.

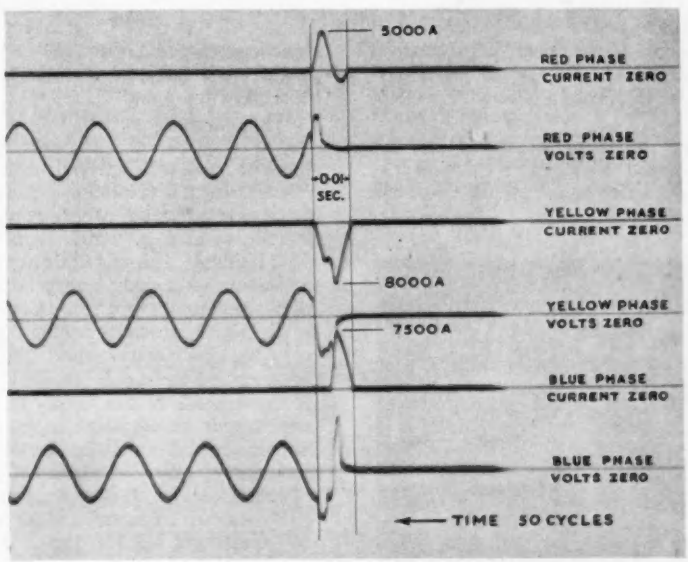

Fig. 12.—Oscillogram of D.C. test on switch-fuse.

Man-carrying Centrifuge

By C. R. DUNHAM, M.A., A.M.I.E.E., Research Laboratories,
and S. A. G. EMMS, B.Sc., Witton Engineering Works.

The very high values of acceleration to which pilots are subjected in modern aircraft has made necessary the investigation of the effect of the resulting forces on the human body and on the various mechanisms with which the aircraft is equipped. For this purpose an electrically driven centrifuge has been installed at the R.A.F. Institute of Aviation Medicine, Farnborough, capable of producing accelerations up to thirty times that due to gravity. Very precise systems of control, observation and measurement enable accurate information to be obtained under any given set of conditions.

INTRODUCTION.

THE development of the gas turbine has made possible the building of aircraft capable of flying at speeds considerably in excess of those attainable with piston-engined machines, and the problems of designing air-frames which can withstand the stresses imposed by the violent acceleration and deceleration of such aircraft, when changing direction at high speed, have, to a large extent, already been solved. To assess the capacity of the human body to withstand these forces is, however, a problem of greater complexity, as tests under actual flight conditions might well cause danger to a pilot with possibly fatal results.

The man-carrying centrifuge described in this article has recently been installed at the R.A.F. Institute of Aviation Medicine under contract with the Air Ministry. All the electrical plant and control gear was supplied by the G.E.C. The design requirements were specified by the Chief Mechanical and Electrical Engineer, Air Ministry Works Directorate, to meet the functional requirements of the Institute of Aviation Medicine, and his division supervised the construction, installation and tests. The centrifuge operates under accurately controlled conditions, and is equipped with apparatus to facilitate medical research into the effects on the human body, and with "teletalk" equipment which enables the subject to describe his reactions to an observer (figs. 1 and 2).

Fig. 1.—A subject in one of the cars of the centrifuge.

The centrifuge is the most modern in Europe, costing some £350,000, and, as indicated, has a threefold purpose : research, clinical investigation and training.

Centrifugal acceleration is measured in terms of the force exerted by the earth's gravitational field denoted by the symbol *g*, which is normally equivalent to 32·2 ft./sec.^{2} Thus 5*g* indicates an acceleration which will exert on a body a force equivalent to five times that produced by gravity. Combat manœuvres, such as high-speed turns or pulling out from a dive, involve very high accelerations and cause a tendency for the pilot's blood to "pool" in the lower parts of the body at the expense of the supply to the brain. The pilot experiences an apparent increase in weight, fatigue, impairment of muscular functions, loss of vision—commonly called "blackout"—and possibly loss of consciousness. It is interesting to note that "blackout" was first encountered to any noticeable extent by pilots training for the 1929 Schneider Trophy race, flying aircraft capable of about 350 m.p.h., when they rounded the turns on the course. These effects are usually of short duration, and it should not be thought that they are experienced daily by pilots in the course of routine flying. Among the vast majority of fit pilots it has been found that there is little significant difference in the amount of centrifugal acceleration which they can withstand.

During the war some research was done on these problems in service aircraft, but the scope of the investigation was necessarily limited as it was found

impossible to install in the aircraft the delicate apparatus required to measure brain and heart functions. It became apparent that a comprehensive enquiry called for the use of special ground equipment operating under controlled laboratory conditions, comprising a centrifuge designed to test the effects of prolonged acceleration so as to enable the physiologists to determine how men should be equipped and clothed, together with details of cockpit design and various other matters concerning the aircraft of the future.

Fig. 2.—The observers at the centre of the centrifuge.

The centrifuge at Farnborough offers tremendous scope for the conduct of much new basic research as well as for the development of equipment designed to increase the safety, comfort and efficiency of aircrew. It does not mark the culmination of aviation medicine ; rather is it a notable milestone in the furtherance of knowledge essential for the advancement of flying generally.

PRINCIPLES OF OPERATION.

The centrifuge (fig. 3) consists basically of a horizontal arm rotating under a precisely controlled cycle of acceleration and deceleration which can be accurately repeated any number of times. The arm, which is approximately 60 ft. long, has a car suspended at each end (fig. 4), and is mounted on a 12-ton flywheel attached to a vertical spindle driving motor (fig. 5) installed in a pit, central in the centrifuge chamber.

Though design problems of considerable complexity had to be solved before details of construction could be settled, the basic theory of the operation of the centrifuge can be stated in simple terms. The cars attached to the arm, when rotated at uniform speed by the driving motor, are subjected to an acceleration, in a direction towards the axis of rotation, of magnitude $\omega^2 r$, where ω is the angular velocity and r the radius of the arm. Thus the magnitude of the acceleration is controlled by the speed of the motor and the effective radius of the arm; consequently, the rate of change of acceleration is governed by the rate of change of motor speed. Each car is mounted on trunnions, fore and aft, so that it can swing out to

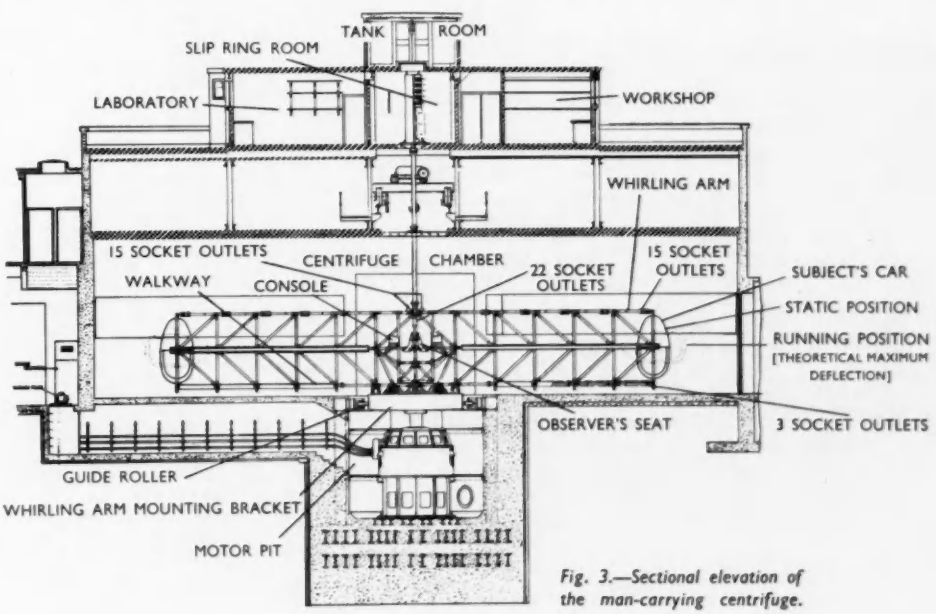

Fig. 3.—Sectional elevation of the man-carrying centrifuge.

maintain the direction of the resultant acceleration on the subject unchanged as the centrifuge speeds up. Hydraulic dampers are provided to check any tendency of the cars to overswing or oscillate. The speed of the motor is varied, in accordance with the programme required, by the electrical control gear, while the arm is provided with a number of attachment points for the cars, so that alternative radii can be selected. At the maximum motor speed of 54 r.p.m. and the full radius of 30 ft., the acceleration produced has a magnitude of approximately thirty times the acceleration of gravity.

The centrifuge can be operated either automatically or manually by a controller seated at his desk in the control room, or by either of the two subjects in the cars. When the two subjects are jointly controlling the speed, the mechanism is so arranged that the speed automatically follows the lower setting, while in an emergency the arm can be brought to rest by the controller, by the subjects or by observers seated at the centre of the arm on either side of the driving spindle. The observers travel round with the centrifuge and each has a clear view of his subject through the " Perspex " roofs of the cars.

To ensure the safety of the subjects and of the mechanical structure, the severity of any run is never allowed to exceed that of a test cycle primarily decreed by the Institute of Aviation Medicine. This specifies the maximum speed of the centrifuge and also the maximum rate of change of speed at any speed.

For certain types of tests, it is possible to remove the cars and, in place of them, erect box-like structures at the ends of the arm. These enable experiments to be performed on the effects of comparatively low accelerating forces on the ability of subjects to perform simple feats involving movement, such as putting on parachute harness. They also enable tests to be

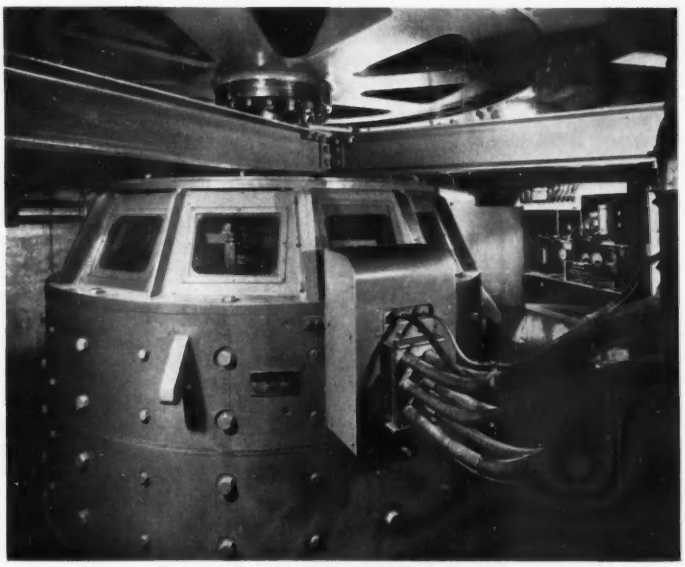

Fig. 5.—The vertical spindle D.C. driving motor.

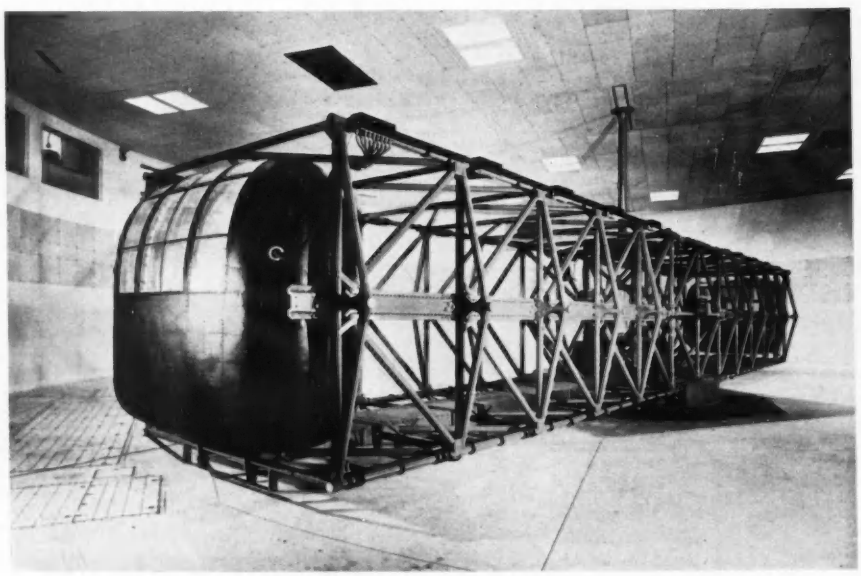

Fig. 4.—The centrifuge, showing the cars at the ends of the arm.

carried out on accelerometers, strain gauges and other mechanisms at high values of acceleration.

PLANT AND CONTROL GEAR.

The main driving motor is a vertical spindle D.C. machine having an overall weight of 46 tons; it is supported on a stool which houses an extension shaft carrying a group of 24 sliprings for providing circuits to the rotating structure for control purposes, lighting and experimental use (fig. 6). The connecting cables pass through the hollow shaft of the motor up to the arm. Half of the sliprings are rated at 60 amp. and the remainder at 30 amp. The motor is fitted with a 12 in. diameter ball thrust bearing of the angular contact type, and with a top roller guide bearing 17½ in. in diameter. The motor is rated at 1,350 h.p., 54 r.p.m., a maximum power 50 per cent in excess of this being developed momentarily at the end of acceleration as the speed reaches 54 r.p.m. The arm is mounted directly on the flywheel and rotates with it at motor speed. A speed increasing worm gear of ratio 3 : 43 is directly coupled to the motor shaft extension below the sliprings (fig. 7). The high-speed shaft of the gearbox drives two tacho-generators and three overspeed devices. Two magslip transmitters are also driven from the motor shaft extension through reduction gears of ratio 2 : 1.

A separate slipring column (figs. 8 and 9) is mounted above the arm in a room over the centrifuge chamber. Adjoining this is a laboratory in which a " recorder " observes readings of all physiological reactions and can intervene to comment on the test or to stop it in an emergency. The slipring column is directly coupled to the arm and is fitted with 60 silver sliprings and 30 mercury troughs for the various electro-medical and teletalk circuits. The sliprings are divided into three banks of 20 rings, and the mercury troughs into five banks of six troughs arranged in pancake form. Two silver-carbon brushes are provided for each slipring, and a spade-type collector for each mercury trough.

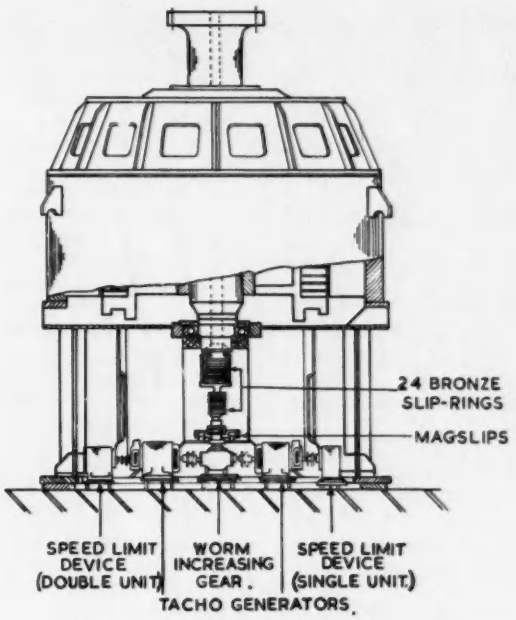

Fig. 7.—Sectional elevation of the driving motor.

Owing to the exceedingly low level of signal strength expected in some of the electro-medical recordings, special care has been taken to reduce the possibility of extraneous interference entering these circuits. Not only is the wiring carried out in individually-screened twisted pairs, but an extensive system of metallic screening has been built into the walls and floors to separate the recording areas from the influence of the heavy current plant and circuits.

The control desk, the amplifier for the teletalk equipment and a cam unit which controls the cycle of acceleration and deceleration, are housed in a control room (figs. 10 and 11) which has a window giving the controller a clear view of the rotating arm in the centrifuge chamber. The controller's joystick is mounted in front of the desk, which consists of two wings joined by a centre section. The centre portion of the desk is equipped with a motor-speed indicator and a "*G*

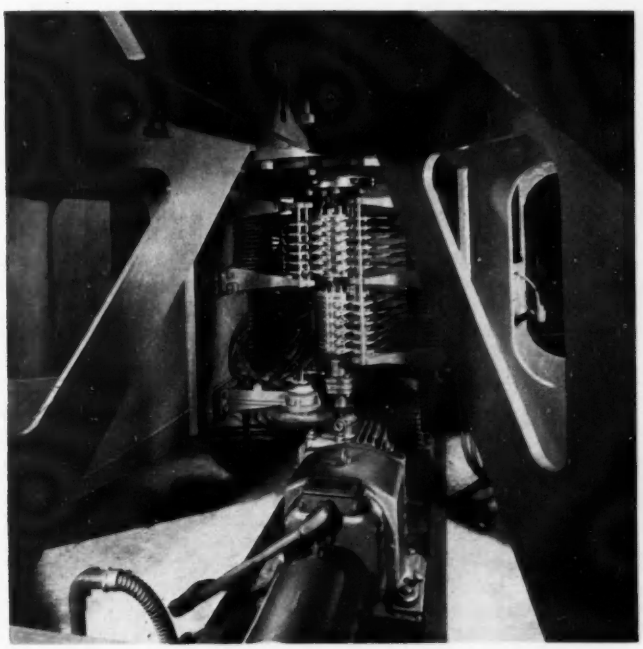

Fig. 6.—The extension shaft below the driving motor with sliprings providing circuits for control purposes.

meter " showing the acceleration to which the subjects in the cars are being subjected ; the wings house the various control equipment for the teletalk apparatus. The cam unit, which is mounted adjacent to the control desk, contains the main control potentiometers and the driving gear for the associated cams, and is fitted with a hinged top cover to facilitate cam changing (fig. 12).

The main control board is of the totally-enclosed sheet steel cubicle type, and contains the contactors, relays and general protective equipment, in addition to the electronic apparatus. It is housed in a plant room (fig. 13) which also accommodates a motor generator set which supplies power to the main driving motor. A cable tunnel runs from the plant room to the motor pit beneath the centrifuge chamber.

The motor generator set consists of a D.C. generator with a maximum rating of 1950 kW at 760 volts, driven at 980 r.p.m. by a 1,250 h.p. induction motor connected to a 6·6 kV, 3-phase supply. The exciter for the field windings of the centrifuge motor forms part of the same set, and is rated at 10 kW, 220 volts.

The teletalk apparatus comprises two separate and similar equipments each providing communication between one arm of the centrifuge with its subject and observer, and the corresponding recording station in the medical laboratory, where the various instruments which record the physiological reactions of the subjects are situated. In addition the controller is provided with facilities for entering each of the two circuits either to listen or speak. In normal use with human subjects aboard, the observer is in control of his teletalk system, and if the controller or the recorder wishes to speak, he must signal his intention to the observer, who will switch the appropriate microphone into circuit. To conserve the available sliprings for their primary electro-medical purpose, and to obviate difficulties due to the effects of centrifugal forces on normal telephone relays, a signalling circuit embodying magnetic amplifiers has been employed.

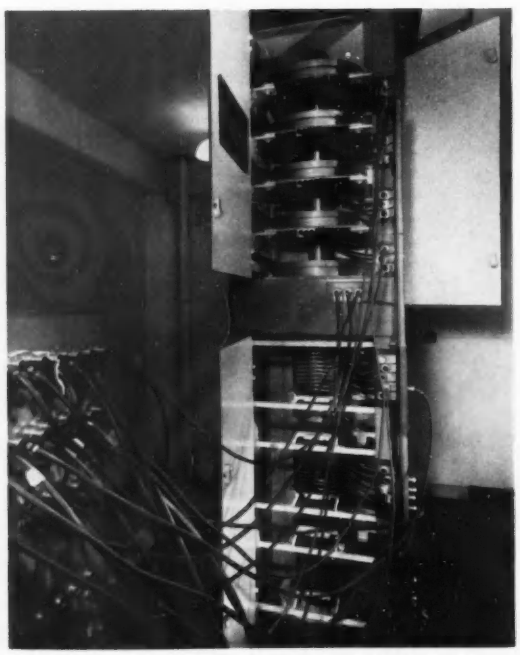

Fig. 8.—Slipring column for medical and teletalk circuits.

THE CONTROL SCHEME.

GENERAL.

A simplified schematic diagram of the control scheme is shown in fig. 14. The armature of the centrifuge motor *M*2 is energised by a generator *G*1 of the main motor generator set, and the field of *M*2 by the constant voltage exciter *E*1. Variation of the speed of the centrifuge motor *M*2 is achieved by adjusting the

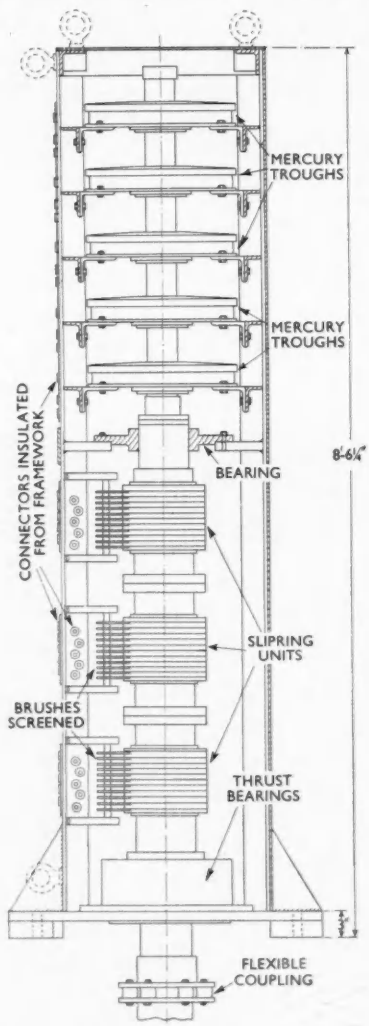

Fig. 9.—Sectional elevation of the slipring column.

excitation of generator *G*1, and hence the voltage applied to the armature of *M*2. This adjustment is made automatically by the electronic equipment in the following manner.

Two separate signals are fed to the input stage of the electronic equipment. The first of these is derived from tacho-generators *TG*1 and *TG*2, which are geared to motor *M*2 and thus develop a voltage proportional to the instantaneous speed of the arm. Two tacho-generators are employed as a safety precaution, and a differential relay connected across them initiates a shut-down in the event of any inequality between the two systems. The second signal is derived from the cam unit, and is proportional to the desired instantaneous speed. The difference between the signals represents the instantaneous speed error, and constitutes the actuating signal to the input unit of the electronic equipment. From this unit the error signal is passed to a two-stage valve amplifier which incorporates a stabilising network for the control system, and hence to the control grids of a 3-phase thyratron rectifier which constitutes the output unit and is used to energise the field of *G*1. The error signal thus varies the excitation of *G*1 in the appropriate sense to correct the discrepancy in motor speed which initiated the signal.

Fig. 10.—Control room showing control desk, teletalk amplifier unit and cam unit.

CAM UNIT.

The cam unit (fig. 15) which provides the " desired instantaneous speed " signal, consists essentially of a pair of potentiometers *P*1 and *P*2, which are traversed by brushes attached to an arm. Movement of this arm is controlled by a programme cam or a stop cam in the manner described below. As in the case of the tacho-generator, two potentiometers are employed to ensure safety, and any discrepancy between the two systems will cause operation of a relay which initiates a shut-down. The potentiometers are bow-shaped and are mounted one above the other ; the effective radius of the brush arm is 24 in. and the total travel between the low and high speed position 41½°. The reference voltage provided from the potentiometers varies from zero at standstill to 400 volts in the high speed position. The signal fed to the electronic equipment is the difference between this and the voltage developed by the tacho-generators, and a difference of less than one volt will result in full excitation of the generator. The arm is moved towards the high speed position by a weight to which it is attached by means of a chain passing over a pulley. The arm bears against the programme cam, which, when rotated, permits the arm to move at a rate dependent upon the profile of the cam. This cam is rotated by an induction motor through a vee-belt drive equipped with multi-step pulleys which enable the appropriate cam speed to be pre-selected. The test cycle of the centrifuge is controlled by the profile of the programme cam, and a range of cams covering the various test requirements is provided (fig. 12).

The second cam, which is called the stop cam, follows the travel of the arm in such a manner that it

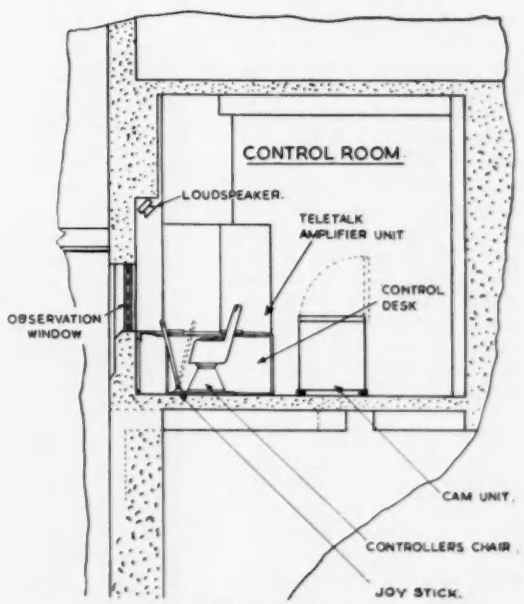

Fig. 11.—Sectional elevation of the control room.

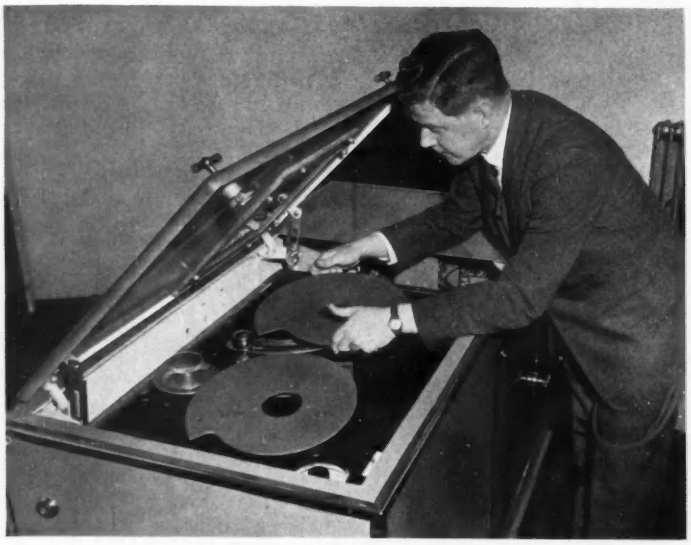

Fig. 12.—Cam unit with cover raised showing the cams being changed.

can take over the duty of pushing the arm towards the low speed position with the minimum of delay. The stop cam cannot be changed, and the speed at which it can move the arm to the lower speed position is fixed by safety considerations. It is brought into action only on failure of the programme sequence, on operation of a " stop " press-button, or when the overall time limit has expired. The stop cam is driven by a direct current motor *M*4. The cam unit includes a series of interlocks to ensure the correct orientation of the cams, and their return to the low speed position for starting. The cam unit is also provided with a series of " *G* plates ", one of which must be inserted before the apparatus can be used. Each plate acts as a definite stop to the travel of the brush arm, and thus limits the maximum speed which the centrifuge can attain to a predetermined value. Plates with stops at 10*g*, 15*g*, 20*g* and 30*g*, are provided.

Programme Control.

The control equipment provides facilities for two automatic systems and one manual system of programme control. The automatic system provides a complete programme of acceleration and retardation from start to stop. The controller may take over control of the arm by operating the manual/auto switch, but if this is done it is not possible to return to automatic control. The automatic control provides for long runs under programme control, without subjects present in the cars for duration tests.

Under manual control, subjects' and controller's joysticks operate " twin-torq " transmitters through quadrants, and associated " twin-torq " receivers impart an equivalent movement to a follow-up drum controller. Although each joystick can be moved independently, the drum controller is so arranged that all three operators must agree to raise speed, but any operator can lower speed in contradiction to the others. If a subject is absent, the relevant switch is closed to short out the interlock circuit ; otherwise both subjects' "dead man's handles " must be retained throughout the run. If either handle is released the controller is warned by an indicator lamp, and he can then take over by cancelling the appropriate handle release. If he fails to take over within 5 seconds the stopping sequence is initiated. Once operated, the take-over circuit cannot be reset until the end of the run. It is a feature of the system that even under manual control, either by the subjects or the controller, the action is always effected through the cam unit. The rates of acceleration and of retardation of the whirling arm and its top speed are therefore

Fig. 13.—Main control board and motor generator set.

limited by the shape of the cam in position, no matter how fierce the operators may be in their handling of the joysticks.

HOMING.

To bring the centrifuge arm to rest in the correct orientation with the doors of the chamber at the completion of each test, the mode of operation of the control unit is automatically changed from that of a speed controller to that of a position controller. This change takes place as soon as the speed of the arm has fallen below a specified value, and the speed of approach of the arm to the home position is then reduced in proportion to its distance from the home position. To achieve this one of the magslip transmitters geared to the centrifuge arm (the other is a stand-by) co-operates with each of the two magslip coincidence transmitters located in the electronic cubicle. As the speed of the arm falls to the given value, a relay operates and causes the reference voltage derived from the cam-driven potentiometer to be replaced by a fixed voltage, so that the arm moves on at a fixed speed. When it reaches a position of 60° in advance of home, the first coincidence transmitter actuates a relay which transfers the control from the fixed voltage to the voltage produced by the second coincidence transmitter, and this is proportional to the displacement of the arm from its final position. The speed therefore diminishes uniformly as the arm proceeds to the home position. Just as it reaches there the second coincidence transmitter actuates a relay which opens the generator excitation circuit, closes suicide windings on both generator and motor, and allows the mechanical brakes to operate.

The centrifuge can be moved into position under "inch" control from push buttons on the control desk; under these conditions the field of generator *G*1 is connected to the constant voltage exciter *E*1 and the electronic equipment is not used.

BRAKING.

The stop buttons and various trips in the stop circuit normally initiate an electrically-controlled retardation of the centrifuge. In the event of a failure of the electronic equipment, operation of an emergency stop button, or the failure of the power supply, the supply to the motor is tripped, and the arm slows down under the action of the mechanical brake, coming to rest without operation of the homing sequence. The control circuit is arranged to ensure that mechanical and electrical braking can never take place simultaneously.

The mechanical braking is hydraulic in action, and is controlled by means of valves actuated by D.C. solenoids. The brake shoes engage with the rim of the

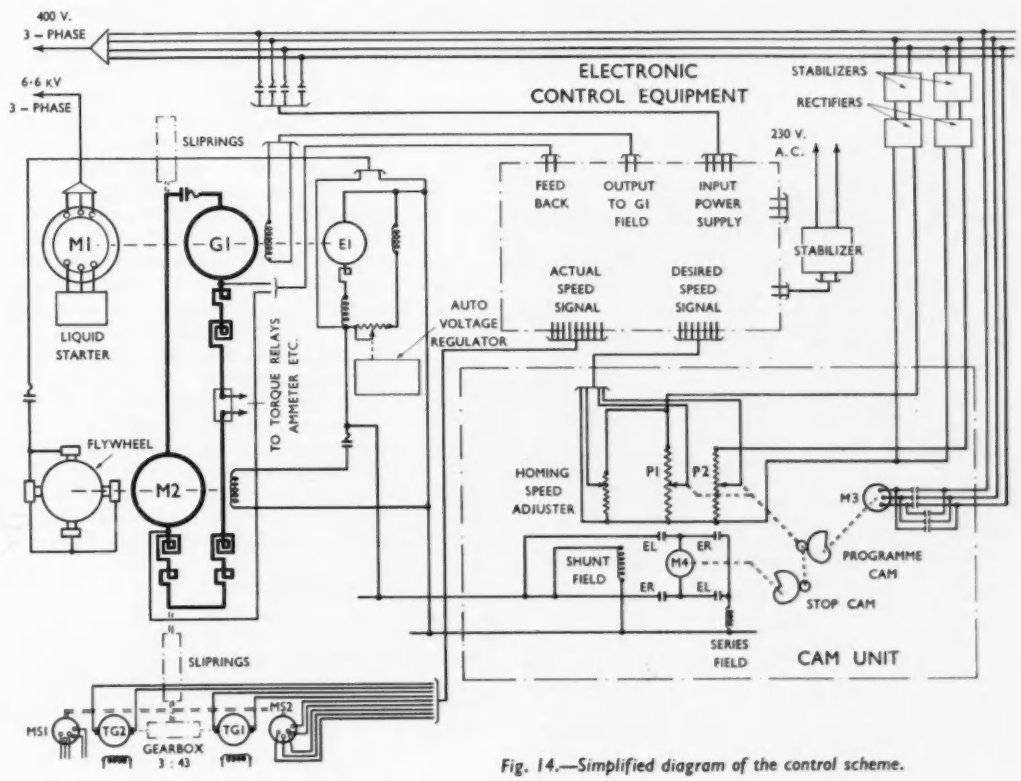

Fig. 14.—Simplified diagram of the control scheme.

flywheel, and are spring-loaded to the "off" position. Under normal stopping conditions the brakes remain inoperative until the arm is virtually "home", when they are applied and used also as "holding" brakes.

Additional Safety Devices.

Although the maximum speed and rate of change of speed are governed at all times by the profile of the cam in use, the control scheme incorporates a number of additional safety features which are described below. These are included to protect the ultimate mechanical safety of the centrifuge, and do not form part of the normal control circuit.

The maximum motor torque is limited by the action of two torque-limit relays which are energised from a shunt in the armature circuit of *M2*. The first relay is set to operate at 101 per cent. of the permissible armature current, and will arrest further acceleration until normal conditions are restored. An adjustable timing relay is started by the first torque-limit relay, and this will initiate the stop sequence if the over-torque condition is sustained beyond the set time. The second torque-limit relay is set at 110 per cent. of armature current, and, on operating, will immediately initiate the stop sequence.

Three overspeed devices are fitted to the centrifuge motor; these are mechanically driven from the high speed shaft of the gearbox. Two are set to operate at 5 per cent. overspeed under normal conditions, and the third operates when the reduced maximum speed permitted when using heavy cars is exceeded by 5 per cent. Operation of any of these devices immediately initiates the stop sequence.

The period for which the centrifuge runs at top speed when under programme control is determined by a programme timer. An overall-time controller, which operates irrespective of the control system in use, is fitted; it consists of two timers covering ranges of 0-100 seconds and 0-100 minutes, the appropriate range being selected by means of a changeover switch. On beginning a run the selected overall timer starts as soon as the raise-speed contactor is closed, and after the set time interval the stop cam is brought into action, unless, in the meantime, the programme timer has operated or the centrifuge has been brought to rest under manual control.

When the programme timer has operated and given a signal to lower speed, the operating coil of a delayed-action checking relay is energised. Under normal conditions the control potentiometer brush starts to move towards the lower speed position, and thus trips a switch which opens the operating coil circuit of the relay before the contacts close. If, however, the brush has not started to move before the relay contacts close, the stop cam is set in motion.

To guard against a transmission failure in the gearbox, with consequent loss of control due to the absence of a signal from the tacho-generators, a voltage relay is set to operate as soon as the main generator attains a voltage slightly above that corresponding to homing speed. A further relay, operated by the tacho-generator and set at the homing speed value, opens the coil circuit of the first relay when conditions are normal, but if the tacho-generator voltage fails the first relay will close as soon as the homing speed is exceeded, and will initiate the stop sequence.

A voltage relay across the output of the main generator is set to operate at a voltage slightly above that required for homing the centrifuge. A normally-closed contact on this relay opens the suicide contactor circuit at all voltages above this value, and prevents suiciding at high speed in the event of failure in the homing circuit. A normally-open contact on the same relay prevents the homing speed reference being given to the electronic equipment at all generator voltages above that required for homing.

An interlock circuit is provided to prevent the centrifuge from being started until the car doors have been locked and the doors leading into the centrifuge chamber have been closed. The chamber doors are then locked electrically and they cannot be re-opened until the whirling arm has again come to rest.

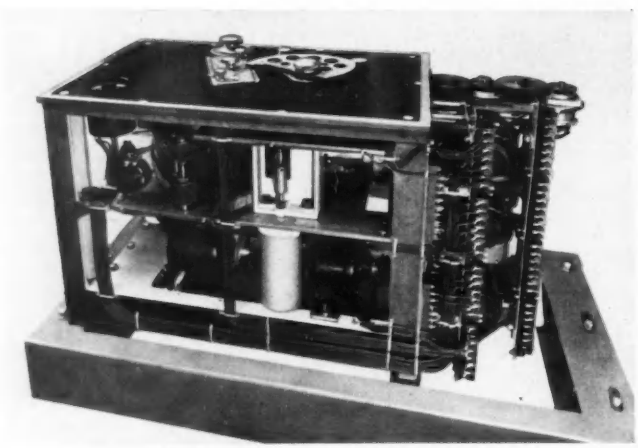

Fig. 15.—Cam unit with covers removed.

The Design of Large Turbo-Alternators

By V. EASTON, B.Sc., A.M.I.E.E.
Witton Engineering Works.

With the demand for bigger outputs from individual generating units, manufacturers are resorting to direct-cooling of the rotors in order to improve the dissipation of the heat from the rotor windings.

In this article the author outlines the steps which have been taken to increase the maximum output obtainable from a given frame size and describes a system of direct-cooling using rectangular copper tubes for the rotor winding which has been developed by the Company.

INTRODUCTION.

IT has generally been accepted that the output which can be obtained from any given turbo-alternator frame is limited by the amount of heat it is possible to dissipate from the rotor without the temperature rise of the windings exceeding the permissible limits. Any attempt to increase the output requires additional excitation power with correspondingly greater loss and higher temperature rise unless at the same time modifications are made to improve the cooling. One modification is the use of hydrogen at ½ lb. gauge pressure in place of air as the cooling medium, and this not only increases the maximum permissible output but also the efficiency. Operation at increasing gas pressures allows greater outputs to be obtained, but at a rapidly diminishing rate as the possible improvement in heat dissipation is limited for reasons discussed later.

Another modification is to bring the cooling gas into direct contact with the copper of the rotor winding. This was proposed many years ago but had obvious disadvantages with air-cooled machines, while the increase in output so obtained would be relatively small. With hydrogen cooling, however, conditions are more favourable, the possible gain is much greater and continues to increase as the gas pressure is raised. Machines using this principle have recently been built by various manufacturers, and while several different arrangements are used, all appear to suffer from various disadvantages, such as discontinuous and unsupported insulation, high excitation current, uncontrolled gas distribution or limited heat dissipation surfaces.

The design described below and developed by the G.E.C.* not only provides most efficient dissipation of the loss in the rotor windings but also a sound practical construction which has many advantages over the normal method of winding. It permits an appreciable reduction in frame size to be made and raises the maximum output of a single unit running at 3,000 r.p.m. to a figure in excess of 200 MW. The weight of the stator is appreciably reduced, and since this is usually the heaviest lift which determines the size of the engine room crane, not only is the latter less expensive but building costs will be lower. Another important point is that the length of the set including space for rotor withdrawal is also reduced. Furthermore, transport problems are eased and the maximum output of a unit which can be conveyed to site in one piece is raised, so deferring the time when it may be necessary to build and wind a stator on site. In most

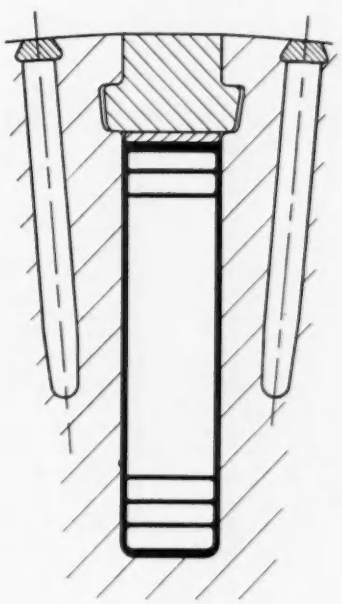

Fig. 1.—Cross section of conventionally cooled rotor slot and ventilating duct.

* British Patent Application Nos. 16236/54 and 16237/54.

cases it is possible with direct-cooling to use a rotor of a smaller diameter and this reduces the mechanical problems and facilitates the selection of suitable materials.

Heat-flow Paths in Rotor.

To appreciate the reason for the great improvement effected by direct-cooling, it is first necessary to consider briefly the heat-flow paths in a rotor of conventional design. Assuming for simplicity negligible flow in an axial direction, all the heat generated in the copper windings in a slot must first traverse the insulation to the surrounding metal. It then passes to the heat-dissipating surfaces of the rotor and through a gas film of relatively poor thermal conductivity before it is absorbed into the main mass of the cooling medium. To transfer the heat energy there must be a corresponding temperature gradient along each of the three sections of the heat path just described and the temperature rise of the copper will, therefore, be the sum of these three gradients plus the temperature rise of the gas.

With the conventional arrangement adopted by the G.E.C., and shown in fig. 1, which utilises deep ventilation ducts machined in the rotor teeth, it is practicable to pass an appreciable volume of gas at relatively high velocity close to the winding slots. As a result the only temperature gradient individually important is that through the slot insulation which may be of the order of 50 per cent. of the total temperature rise of the copper. The chief effect of the substitution of hydrogen at $\frac{1}{2}$ lb. gauge pressure for air as the cooling medium is to reduce the temperature rise of the gas and the heat transfer gradient at the duct surfaces relative to that through the slot insulation. Operation at higher absolute gas pressures in the casing will reduce these still further until they become a small proportion of the total temperature rise of the copper. There is, therefore, a very definite limit to the additional output which can be obtained by this means, and it is generally considered that a gauge pressure of 30 lb. per sq. in. is about the maximum which can be justified with conventional cooling.

However, when the cooling gas is brought into direct contact with the copper, in sufficient quantity and at a reasonably high velocity, very different conditions are obtained. The heat generated in the windings is now dissipated directly to the hydrogen, so eliminating the previously important limiting factor of temperature gradients through the insulation and steel, and the temperature rise of the copper depends only on that of the gas and on the heat transfer drop at the duct surface. Since both these factors are affected by the absolute gas pressure, theoretically there is no limit to the higher excitation powers which are permissible with correspondingly greater outputs as the pressure is raised, but in practice other design and constructional features, such as efficiency and stray losses must be considered. Fundamentally, however, direct-cooling is most advantageous when the gas pressure is high, say, 30 lb. per sq. in. or above.

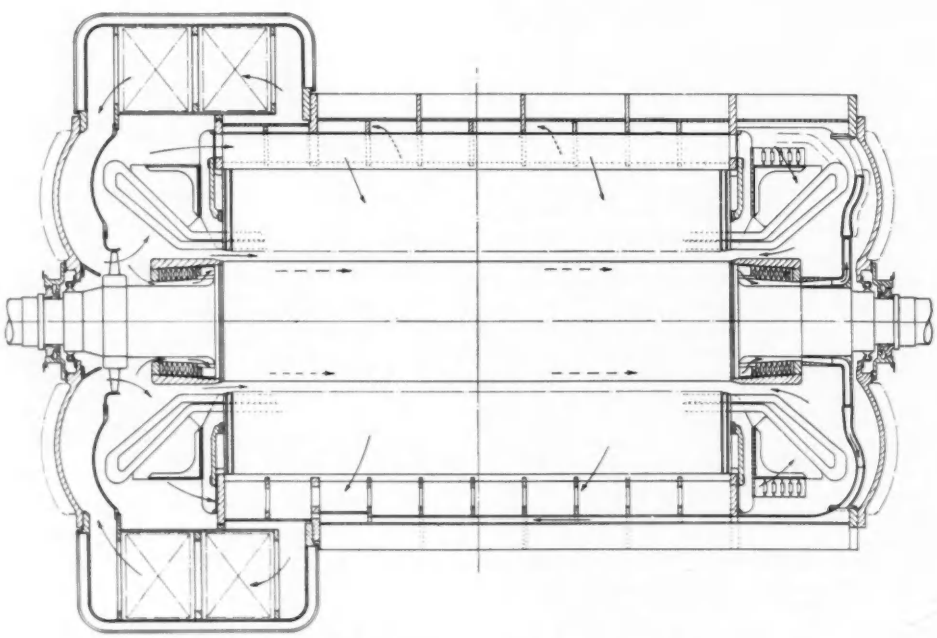

Fig. 2.—Gas flow through a G.E.C. direct-cooled alternator.

CONSTRUCTION OF DIRECT-COOLED ALTERNATORS.

The essential feature of the G.E.C. direct-cooled alternator is the use of straight rectangular tubes for the slot portions of the rotor windings ventilated on a separate circuit from that of the stator, the hydrogen being circulated through the tubes by a centrifugal impeller mounted on the outboard end of the rotor. The stator ventilation is substantially similar to a conventionally cooled design except that only one axial flow fan is fitted and the ventilation ducts are modified to suit the single end entry. Uniform temperature along the stator is still maintained. The two parallel paths for hydrogen flow will be clear from fig. 2, a general arrangement drawing, while fig. 3 shows in more detail part of the windings at one end of the rotor including the gas entry (or outlet) ports in the overhang portion. The slot tubes are connected at both ends by suitably shaped copper strips and these are also direct-cooled on separate circuits (not shown in fig. 2) so increasing the effective volume of hydrogen flowing through the rotor and reducing both the maximum and mean temperature rise of the windings.

The general arrangement of the conductors in the slots is shown in fig. 4. The slot itself is parallel sided and is wider at the top to provide the maximum area for copper and gas ducts. The conductors are hard-drawn tubes of electrolytic copper alloyed with a small proportion of silver in accordance with usual practice to improve the mechanical properties at elevated temperatures. As explained later this is not essential but is an additional safeguard. The conductors are made in straight lengths and credit is

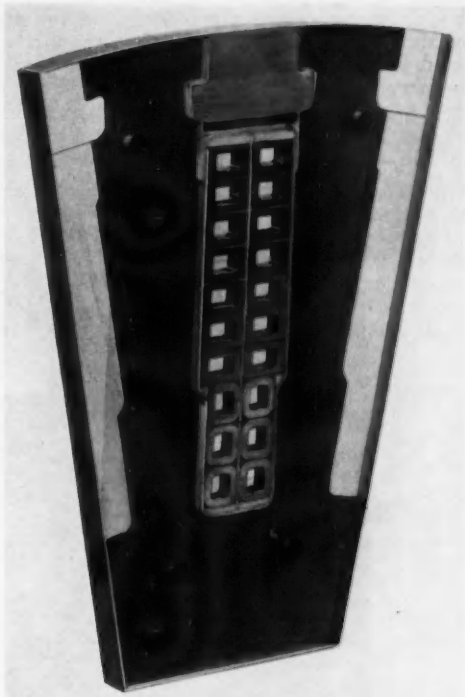

Fig. 4.—Jig assembly showing arrangement of the conductors and insulation in the slot.

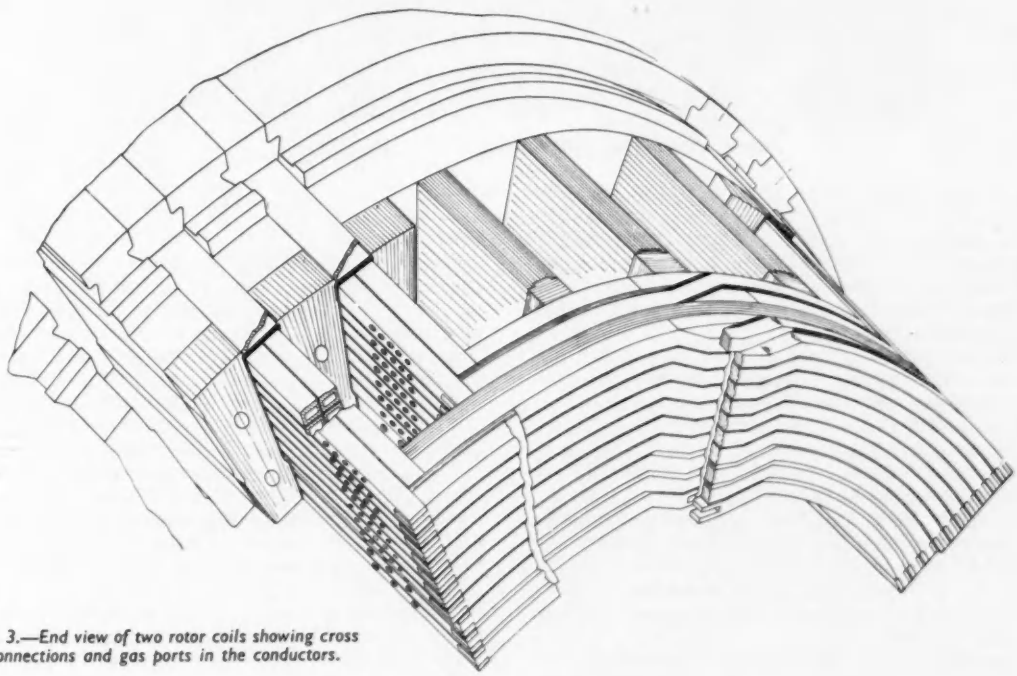

Fig. 3.—End view of two rotor coils showing cross connections and gas ports in the conductors.

due to the manufacturers who tackled a difficult problem, and after much experimental work, produced tubes to a close tolerance on overall dimensions which fully met the specification. The square tubes at the bottom of the slot have walls of equal thickness on all sides, but the rectangular tubes have been produced with side walls of about 40 per cent. greater thickness than the top and bottom and with only a small radius on the outer corners. Since the centrifugal force on all the lower conductors is supported by the side walls of the top conductor an increase in thickness is very advantageous and provides an ample factor of safety at this point.

The arrangement of two conductors side by side has the advantage that the number of turns per slot is not reduced compared with a conventional winding and the increase in excitation current is only moderate. At the same time, gas ducts of reasonably efficient aerodynamic shape are obtained and the mechanical stresses in the copper are low.

As will be clearly seen from fig. 3, the end connectors are not tubular but consist of strips which are formed on steel jigs and, while clamped in position, the ends are machined to size so ensuring accurate assembly on the rotor and uniform support of the windings by the end bells.

The conductors are fitted into the slots and the end connector joints are made in a definite orderly sequence. The connectors are fitted to the bars at right angles, with an interleaved joint secured by silver soldering, using the brazing technique which has been standard practice for many years for stator winding joints. This procedure ensures that there is no distortion of the copper and no deterioration of the insulation which is inserted after the joint has been made and as the winding proceeds.

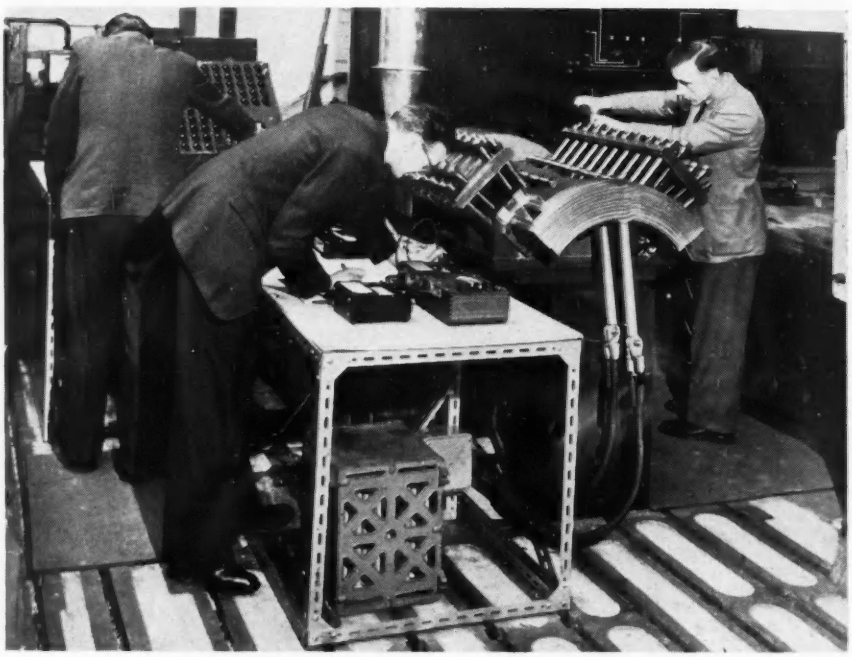

Fig. 5.—The test set-up of two coils in the Witton Laboratories.

INSULATION.

One of the objects kept prominently in mind when developing the new winding construction was the possibility of eliminating micanite as the main insulation. Micanite has been used for a great many years and its general properties are well known, but it was felt that one of the more recently developed materials might overcome some of its disadvantages. After full investigation, a synthetic resin bonded glass cloth laminate was selected for the insulation. The material has high electrical and mechanical strength, a reasonable degree of flexibility, and is unaffected by temperatures well above those normally experienced in operation. The surface finish is smooth and hard and is well able to withstand frictional forces such as may arise when fitting the conductors tightly into the slot. In general, the insulation is used in a double thickness both to earth and as a separator in the centre of the slot. The divided separator permits the insertion of narrow packing strips between the two halves prior

to fitting the second conductor in any layer should it be necessary to compensate for any tolerance in the machining of the slot and in the overall dimensions of the copper which otherwise might lead to slackness of the conductors. The interturn insulation is also in two layers with staggered butt joints to maintain uniform thickness.

PRACTICAL ADVANTAGES OF CONSTRUCTION.

The arrangement whereby the hydrogen is drawn from one end of the rotor to the other has many important advantages.

It permits the use of continuous slot insulation with normal creepage surfaces, and eliminates any discontinuity or bushings necessary if the gas is drawn in at each end of the rotor and discharged into the gap. Furthermore, the slot and interturn insulation is formed from rectangular strip material and is contained between continuous flat surfaces.

The ports for gas entry into, and outlet from, the slot conductors are in the side walls of the tubes outside the rotor body (as shown in fig. 3) in a position where the metal is uninsulated. The gas flow, therefore, cannot be restricted by relative movement of the copper and the insulation.

The temperature rise of the stator is unaffected by the loss in the rotor windings since all the heat absorbed by the hydrogen passing through the tubes is carried direct to the gas coolers. In view of the greatly increased excitation loss permissible with direct-cooling, this is of particular importance.

The cooling surface of the conductor exposed to the gas is large so keeping the temperature difference between the copper and the hydrogen to a minimum and rendering this factor relatively insignificant in relation to the mean temperature rise of the rotor winding.

The chief factor affecting the temperature rise of the winding is that of the hydrogen as it passes through the conductor tubes. With the arrangement shown in fig. 2 complete control is possible to equalise the volume of gas flowing through individual conductors. As the gas inlet temperature is also the same for all conductors, the ideal condition of uniform temperature from top to bottom of the slot is obtained.

On the practical side, in addition to the major advantage of pre-formed windings which can be assembled without distortion, there will be no local concentration of mechanical stress in the rotor wedges or teeth such as will arise with radial ducts discharging the gas into the gap.

PERMISSIBLE OUTPUT WITH DIRECT-COOLING.

It has been mentioned that with a direct-cooled machine the frame size required for a specified output is not influenced by the temperature rise of the rotor but must be determined from other considerations, the two most important probably being the efficiency and the stray losses. Any reduction in frame size necessarily means increased specific loading of the stator, and consequently an increase in the stray losses. On the other hand, the greater length of gap required at these higher ratings to retain the specified characteristics has the effect of reducing these losses so that the nett increase is only moderate.

With regard to the efficiency, a reduction in frame size is obtained at the expense of increases in excitation power, stray loss and stator copper loss which are approximately compensated by reductions in iron and friction losses. The variable losses, however, are now a greater proportion of the total loss and their rate of increase will exceed that at which the fixed losses diminish as the frame size is made smaller. The final result is a fall in efficiency, the amount of which is dependent on the extent of the uprating of the frame, but may be influenced by the use

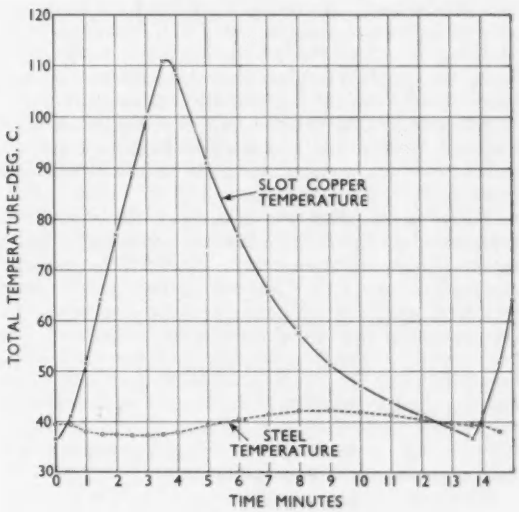

Fig. 6.—Typical thermal cycle during initial test.

of better quality materials. As the load is reduced, the difference in efficiency between the conventional- and the direct-cooled machine tends to become less, as the fixed loss of the latter is the smaller, and a point will be reached when it becomes the more efficient. The direct-cooled alternators at present under construction by the Company have a calculated full-load efficiency closely comparable with that of the corresponding conventionally cooled machine.

The reduction in frame size made possible by the direct-cooled rotor is large and the corresponding stator loading is so much greater than with the present standard alternators under rated conditions that the designer would normally hesitate to extrapolate test data to the required extent. Tests already made in the Witton Engineering Works, however, on conventional 75 MVA alternators with heat runs up to 100 MVA which correspond approximately to the normal loadings proposed for alternators designed by the Company for outputs up to 200 MW, have demonstrated that stators of standard design will be entirely satisfactory.

Voltage Response.

One of the important technical advantages of the direct-cooled alternator is the more rapid response of the A.C. voltage to changes in excitation compared with a conventional machine. This is due to the higher permissible rating of the field windings and results in a reduction of about 50 per cent. in the rotor time constant. Since the latter represents by far the biggest individual time constant in the voltage control circuit the effect of this reduction in improving the stability of the machine will be readily appreciated.

Model Tests.

Two complete rotor coils using full-size copper sections were assembled and subjected to exhaustive mechanical tests. A steel jig, about one third the length of a 60 MW rotor, was fabricated to support four rotor slots and into these the two complete coils were wound using the specified conductors and insulation. Advantage was taken of the opportunity to develop a suitable winding technique prior to the manufacture of production machines but very few problems arose and the second coil was wound and insulated in a remarkably short time.

When the winding was completed, the model was transferred to the G.E.C. Witton Laboratories and a massive clamping arrangement was fitted to compress the conductors in the slots so simulating the effects of centrifugal force. The load on the clamping bolts was measured by individual strain gauges totalling over three dozen so that complete control of the loading was possible. The windings were connected to a low voltage, heavy current D.C. supply and a special blower was erected to draw air through the conductor tubes. Fig. 5 shows the model and associated test equipment in the Witton Laboratories.

After preliminary tests had been made, the windings were subjected to automatically controlled thermal cycles, the temperature of the copper first being raised rapidly to a value much above the operating conditions with no cooling on the model. The current was then interrupted and the blower run to cool the copper in the shortest possible time, the temperature of the copper being checked along the length of selected bars by thermocouples built in as the winding proceeded and also by means of voltage tappings on other bars from which the resistance and mean temperature could be calculated. Since, in the model, the end connectors are not ventilated they eventually reach a higher temperature than the tubes and a measurement of the average temperature of the whole winding is not sufficiently accurate.

A typical thermal cycle taken during the initial testing is shown in fig. 6.

As the duration of the cycle is less than 15 minutes, and since it is running night and day, the time multiplier even for a machine on two-shift operation exceeds 1 : 100. These thermal conditions are, of course, much more severe than would occur in practice, since in no power station will full-load excitation suddenly be switched on to an unloaded machine. Periodically the insulation is examined for signs of deterioration but, up to the present, none has been found ; the tests are proceeding on a long term basis and with higher temperatures in order to establish operating limits.

Units embodying direct-cooling with outputs of 60 MW and 120 MW are now in course of construction at the Witton Engineering Works.

CONCLUSION.

The advent of the direct-cooled machine has revolutionised preconceived ideas of machine design and has led to a material increase in the output of turbo-alternators. Factors other than the rotor temperature rise now determine the size of machine and obviously further development will raise the present limiting values of these factors and pave the way to further increases in output.

It has been the object of this article to give a general picture of the work now being done in this field. Progress is rapid, however, and considerable advances are likely to be seen in the near future.

The Collection, Presentation and Study of Data in Relation to Industrial Efficiency

By B. P. DUDDING, M.B.E., Ph.D., A.R.C.S., F.Inst.P.
Research Laboratories.

INTRODUCTION.

IN the course of industrial activity, decisions have to be made by persons holding positions of widely different degrees of responsibility such as: supervisors of machines and processes, production engineers, sales superintendents, and more senior executives. Decisions are made as a result of observation, even in those cases where observations play an indirect part and are gathered up in the term "experience." The quality of a decision in relation to the circumstances it is taken to meet will depend on the quality of the observations, of the methods adopted for collecting and recording the results of the observation, and of the consideration and study devoted to them.

A number of articles has appeared in this Journal[1-8] illustrating the important contribution which the proper collection, presentation and study of data can make to industrial efficiency. Work of this kind is to-day carried on in many organisations under such titles as: Quality Control (used in a broad sense), Production Study, Operational Research and Market Research. The methods and techniques are based on statistical principles which have been known for a very long time, but the application to industrial problems is quite a recent development. Learned philosophical discussions appear to have delayed practical application far more than the controversy about the modes of propagation of light through transparent media delayed the development and use of optical instruments.

There is no doubt that the practical application of statistical methods in industry has been greatly retarded by the use of the word "statistics" in this connection, before students in schools, colleges and universities had been introduced to the mode of thought which is essential when drawing conclusions from the study of data, one of the principal characteristics of which is their *variability*. The word "statistics" often brings to mind masses of figures which are selectively used to support conflicting views. Not infrequently these masses of data have little relation to the science of statistics, either in their mode of collection or their presentation, and have therefore little value as a basis of study. Fortunately the efforts made to introduce students to the rudiments of the science during the past decade are removing some of the obstacles which impede practical application, but very much still remains to be done.

It is about thirty years since the first steps were taken in the G.E.C. to apply statistical methods to the study of data collected as a routine in factories, and to develop methods of presentation which would assist all concerned with the supervision of manufacture. These early efforts derived their inspiration from work done in 1912-14 when Sir Clifford Paterson, the late Director of the G.E.C. Research Laboratories, and the writer were collaborating at the National Physical Laboratory in the task of setting up an International Standard of Light. This work was the subject of a paper given before the Physical Society of London in 1915[9] and includes a table which would have a familiar appearance to the present-day student of statistics. In this, the total variability in a comprehensive series of photometric measurements was divided into three parts:

(*i*) the variability associated with the observations made by one observer in one day;
(*ii*) the variability associated with the observations made by an observer on different days;
(*iii*) the variability associated with the measurements made by different observers.

APPLICATION OF STATISTICAL METHODS TO INDUSTRIAL PROBLEMS.

The variability always found in the technical characteristics of manufactured products makes their inspection necessary. In the early years of this century and during the first World War, manufactured products of all kinds were very often subjected to 100 per cent. inspection after production. Sampling inspection was of necessity used in the case of destructive testing, but the limitations involved when drawing conclusions from such testing of samples were practically unknown or ignored.

Efforts to reduce the amount of final inspection by the use of methods based on statistical principles appear to have been made at about the same time in the

U.S.A. and in England. In America, under the inspiration of Dr. W. A. Shewhart, systems of sampling inspection were introduced that would minimise the amount of inspection necessary to reduce the proportion of unsatisfactory products in an accepted batch to a predetermined value. The Dodge-Romig sampling inspection tables[10], first published in 1929, became well known during the recent war and were supplemented by the double sampling tables[11] issued during the war[12].

During the last thirty years, statistical methods have been introduced and used in many of the G.E.C. factories[1-8]. They have also been used to assist forward production planning and in the sales organisation. Those who have had first-hand experience of the methods have always found them useful, but there is still much that can be done. The principal obstacle to their more general use is that so few of the persons who occupy positions involving supervision of machines and processes have had, or can obtain, training in the rudiments of statistical methods of thought.

Within the G.E.C., statistical principles were used to devise methods of aiding the direct study of the performance of machines and processes rather than on the examination of the finished product. The guiding principles can be briefly summarised as follows :

(*a*) In the light of the difficulties encountered during production and the technical and scientific knowledge of the procedures, introduce as a routine measurements of appropriate features of the machines or processes. The measurements should be in small groups made periodically, ranging from an hour to one day depending on the nature of the production. In many cases, the measurements are associated with the product of the machine or process, but it is important to realise that this is not absolutely essential and that other features of the machine or process are sometimes more convenient to measure and provide more valuable information.

(*b*) Use graphical or pictorial methods of presenting data which would assist supervisors of all grades to differentiate between important and unimportant variations in results and to recognise the onset of changes which would ultimately give rise to serious difficulties unless action were taken early enough.

(*c*) Use the foregoing visual aids to encourage and stimulate intelligent interest of all concerned in the work of the factory, and to reduce the inevitable tendency of everyone to attribute his difficulties to someone else and to overlook contributions that each may make to smooth and efficient operation of the factory.

It is not, of course, possible to lay down precise rules to suit all organisations even in the same industry. There is much scope for ingenuity in devising the methods of measurement and in the selection of the item to be measured. Ultimate success can only be achieved by close co-operation of persons performing different functions and operating in different sections of the factory. The major problems in industry are not necessarily technical but frequently reside in the field of personal relations.

Another problem inherent in the successful and widespread use of these methods is that the science of statistics is basically mathematical, and hence there is a marked tendency to associate even elementary instruction with mathematics. Since extremely few of the teachers chosen for this work have any industrial experience, the classes often have little appeal for those who would seek training and would undoubtedly benefit from the ability to think statistically. Further, in the absence of some elementary training in the application of statistical methods to the study of data, many of those having both industrial experience and sufficient knowledge of statistics find the task of stimulating interest in statistical methods among industrial workers and supervisors a severe strain on their powers of patient endeavour. Neither can it be claimed that the majority of those in more senior positions give sufficient encouragement either to the few that would bear the burden of teaching, or to the many who would seek instruction when it is available.

A more detailed description of each of the principles outlined above may be helpful in showing how these problems may be overcome :

Choice of Item to be Measured.

It is generally impossible, and somewhat unwise initially, to introduce sampling inspection of this kind on a very comprehensive scale. Detailed examination of existing records, or a discussion of scientific knowledge and of past experience by a group of experienced persons, will indicate where sampling inspection might prove helpful. It is certainly true that it is difficult to avoid such preliminary examinations and discussion being unduly influenced by the prejudices of those concerned, and the best choice may not be made because of tactics adopted as measures of defence against criticism. Nevertheless, experience in a large number of organisations engaged in very different classes of manufacture has demonstrated that the procedures advocated here reduce the influence of these less helpful attitudes and lead to better mutual understanding and finally to a good choice of the points at which sampling inspection is used. More important still, a broadly based critical attitude is developed which leads to continual adjustment of the procedure to meet developments in the industry, promoted either from within or without.

Presentation of Results.

There is not the slightest doubt that the " Control Chart " first described by Shewhart in 1926 provides an ideal medium for presenting the results of sampling inspection or of any series of factual data. The method adopted in the G.E.C. and described in B.S. 600R (1942)[13] simulates the methods for studying data initiated by " Student "[14] and developed by Fisher[15] whose first paper appears to be one published in Vol. II of the *Journal of Agricultural Science*, 1920. By basing the procedure on groups of measurements, which involve a time relatively short compared with the period between the successive groups of measurements, an estimate can be made of the variability inherent in the process concerned and is akin to the " residual " in analysis of variance procedure. The limits drawn

on the control chart are based on this measure of variability and serve to indicate when some extraneous factor is influencing the results, thus drawing attention to the need for critical technical examination and appropriate corrective action.

If the measurements being made are related to the characteristics of a product which are the subjects of a specification or some other defined objectives, the estimate of the magnitude of the variability inherent in the process concerned can be used to classify the process relative to the specification. This technique was first described in the handbook "Quality Control Chart Technique when Manufacturing to a Specification"[16], and has undoubtedly proved useful in many industries because it indicates clearly the nature of the shortcomings of a process if consistent conformity to specification is difficult to achieve.

Encouragement of Interest.

It should be emphasised that the greatest service that control charts can provide is lost if they are merely kept in the office or desk of a supervisor. In their simplest form, they should be exhibited in the organisation in close proximity to the process from which the data were derived. On many occasions, both in G.E.C. and other factories, the exhibition of results in this manner has raised efficiency by creating an interest for operators of modern processes where the nature of the process has eliminated the kind of interest which was inherent in the work of the artisan. In addition, exhibition of control charts in different sections of a manufacturing organisation does much to reduce inter-departmental suspicions, and to discourage the practice of "passing the buck".

G.E.C. STATISTICAL SERVICE TO INDUSTRY.

Facilities for Industrialists to acquire Statistical Knowledge.

The use of statistical methods within the G.E.C. has inevitably exerted an indirect influence on the more general applications of these techniques in English industry. In addition, however, the Company has also played a major part in activities whose object has been to acquaint industrialists with statistical methods.

At a meeting held at the British Standards Institution at the time Dr. Shewhart visited England in 1932, it was suggested by the writer that the Royal Statistical Society could stimulate interest in the use of statistical methods by forming a section devoted to their use in industry. At the same time, the B.S.I. also considered the formation of a Committee with similar aims.

This meeting led to two important developments :

(*a*) The Royal Statistical Society formed a section entitled "Industrial and Agricultural Research Section" in 1934 and from then on published the proceedings of the Section in a supplement. These supplements contain papers of great interest and value to industrialists, but it is true that many were of too advanced a nature to serve as encouraging instruction to those without a knowledge of the science of statistics. Although this section ceased to function when war broke out in 1939, a series of discussion meetings held under the auspices of the Royal Statistical Society was inaugurated by G.E.C. staff in 1942, following considerable publicity given to the use of statistical methods in the U.S.A. These discussion meetings dealt with the most elementary application of statistical methods, and particularly with the techniques often referred to as "Quality Control". (It is unfortunate that the word "Quality" has always been associated with Control Chart Technique, for this association undoubtedly retarded the application to other classes of industrial data where its use would have been as valuable as, or even more valuable than, in the narrow field of factory inspection.)

At the end of the war and again at the writer's suggestion, the Royal Statistical Society agreed to create a section devoted especially to industrial applications. The original Industrial and Agricultural Research Section was subsequently replaced by three others known as : Research Section, Study Section and Industrial Applications Section. The staff of the G.E.C. Statistical Service has played a leading part in the activities of these Sections, as well as of the regional groups of the Industrial Applications Section. Seven such regional groups were started outside London between 1945 and 1952, as a result of the success achieved by several technological societies in bringing their meetings within easy reach of those engaged in local industries. Several conferences have also been associated with the work of this Section, after one of which the Royal Statistical Society launched a new journal, *Applied Statistics*, in March, 1952.

(*b*) The formation of the B.S.I. Committee in 1934 led to the publication of B.S. 600 (1935) which gained world-wide approval. When the type was destroyed by enemy action, B.S. 600R (1942)[13] was prepared to meet the particular needs of the time, and this has enjoyed a popularity similar to that of its forerunner.

In addition, practical experience in the engineering industries between 1942 and 1944 revealed the need for a small handbook of instructions to assist those holding junior positions of responsibility in constructing control charts. To meet this need, the G.E.C. Research Laboratories published the handbook entitled "Quality Control Chart Technique When Manufacturing to a Specification"[16] in 1944. A ready method for classifying the quality of a process relative to a specification was first published in this handbook. This had proved particularly valuable during the previous two years' experience in factories making munition components, and has since found quite general application. This handbook has also found wide acceptance and has now been published as B.S. 2564 (1955).

Allied with the more formalised activities described above, the staff of the G.E.C. Statistical Service has for many years been active in what might be termed general educational work with the aim of supporting all efforts made to develop the use of statistical methods in industry. A summary of much of this extramural work has been given earlier.[7] Since that time, these activities have continued and indeed increased. Not only have lectures been given to groups of persons in technical colleges, and in a large variety of works,

but assistance and initiation of control chart techniques given to inspectors and production engineers. During the last eight years, lectures illustrated by slides and experiments have been given in many universities and technical colleges, and indeed some have become a permanent feature of the curricula of such colleges. There have also been special day conferences which have drawn large audiences and promoted valuable discussions.

Facilities for Direct Assistance to Industry.

Arising out of all the foregoing activities, many requests for assistance have been received from other manufacturing organisations. These cover a great diversity of industries, for example : canning, ceramic (glass, white ware and heavy clays), confectionery, cosmetics and washing materials, chemical, electronic and general engineering, founding, horological, photographic, iron and steel, vitreous enamelling. The methods introduced have rarely been jettisoned once they have been installed, although progress has often been slow. The principal causes of this have already been mentioned : first, lack of suitable training during earlier education or at evening classes for those now in the 30-45 age group ; second, lack of patience and encouragement by senior management who appear to expect the difficulties which have beset their industry for years to be overcome in a few weeks. No such panacea exists. Success requires patience, goodwill and much thoughtful work by all who carry responsibility in a manufacturing concern. Illustrating the successful application of these techniques in widely differing fields, three examples have been chosen from among the many in which assistance has been given.

Confectionery.

In this concern, the introduction of statistical methods was due to the initiative of a young engineer who had attended a short series of lectures given by the writer, who was then invited to visit the factory. A series of lectures given in off-duty hours to about twenty members of the staff, followed by keen and thoughtful application to a wide diversity of operations, yielded valuable results before the expiration of a year. In this example, the existence of a lively team spirit in the works greatly eased the difficulties so often experienced in introducing statistical methods, so that the staff were able to operate the schemes successfully without outside assistance in about two years.

The reactions of a few members of the staff, following these lectures, are of interest in that they show how quickly the basic principles of the method are grasped :

(*i*) " 'Averages' thrown up from production batches are not always what they seem. Many respectable averages, when put into the statistical dock, are found to have criminal associates."

(*ii*) " Samples should be taken in small doses and often. More is learnt from 10 samples of 2 every half-hour than 1 sample of 20 every 5 hours. Further, inferences can be drawn more quickly, and action can be taken before serious trouble has developed."

(*iii*) " Samples should be used like signposts to find out where one is going, not where one has been. In other words, they should be prophets, not historians."

The principal application of the control chart technique in this factory has been to control the size and weight of sweets or parts of sweets. At nearly all stages in the manufacturing processes, charts are now used to record the weights of small samples of the product taken at frequent intervals throughout the day. Any trend away from the target weight can thus be quickly seen and corrected by the operators responsible for the process.

The same technique is used to some extent in controlling the weights of all the major moulded lines. In some instances, the supervisor responsible for the moulding unit uses a modified control chart combined with specific instructions as the basis for his adjustment to the depositor. On another unit, the final weight is not determined until a later stage, but it is possible to plot the weight of the partially moulded blocks during the various processes on control charts. In all cases, the supervisors can see at a glance how the " run " from the beginning of the shift is proceeding and what the current position is.

On the packaging side, the most important innovation has been individual weight control charts for use by operators who weigh assortments sold as " net weight " lines. When first introduced, these charts, which are kept in frames attached to the work benches, brought to light an astonishing variation between the average overweights given by different operators. Each chart is now examined at regular intervals and an assessment of its quality passed to the operator by a supervisor. This technique of collating and exhibiting individual results has considerable value in a large quantity-production department where the identity of the individual can so easily be lost.

Applications of statistical methods have also included investigations into significance and correlation of results of carriage tests, tasting panels, the design of an "embargo" scheme, a periodical independent check on the " spread " of weight of moulded lines and the feasibility of proposals for bonus schemes based on output.

Light Ceramics.

The pottery industry, and particularly that section devoted to the manufacture of table-ware, has long accepted the fact of a very high degree of loss during manufacture. It is in fact considered normal to receive only 80 per cent. of the goods that commence manufacture when the final sale is reached. In addition, a very high degree of variability is present in the quality of the goods themselves, so that any technique which can be used to reduce these losses and control the quality is likely to show an immediate and large financial benefit. There is no lack of data available in the industry or in a particular plant, but such

figures have all given a record of past actions and give very little guide to future action.

In the plant under consideration, it was felt that the control chart methods described in B.S. 600R could be of assistance in this direction, and the advice of the G.E.C. Statistical Service was sought. A first visit resulted in a very convincing demonstration of statistical methods. It was clearly shown from the figures already available that their movement, which had previously been taken as an indication of an improvement, was no more than an indication of the normal variation inherent in the manufacturing process. This initial introduction led to the attendance at lectures of a team drawn from the staff and, as a result, control charts began to be used in the works.

The original tendency was to measure quantities towards the end of the production line, but experience showed that, to improve the degree of stability, measurements would have to be made further and further back in the process. A very large number of measurements are now recorded on control charts which become increasingly valuable with time and give a much clearer picture of the inter-relationship between the various phases of manufacture. Such items as indication of seasonal trends can also readily be seen.

Building Bricks.

Soon after the war, a brickmaking concern became interested in the use of statistics as a research tool. Early progress in this direction was not particularly promising, partly because the initial approach was too closely allied to academic procedures and was at too advanced a level. In fact, the conclusion was almost reached that quality control charts techniques could be only applied to industries with the production of parts or components machined to fine engineering limits, and could not be applied to such craft industries as brickmaking.

At this stage, contact was made with the G.E.C. Statistical Service and it is fortunate that this collaboration was begun at the same time as a new British Standard for the size of common building bricks[17] was published. As stated in its foreword, this Standard was based on statistical concepts, so that this company, faced with the necessity of judging its finished products, was to that extent forced to adopt some statistical approach.

After making a survey of the process and holding detailed discussions with those having long experience in the industry, a modest scheme of inspection of the first product was introduced. This was coupled with the systematic recording of essential changes in the process as affected by raw material supplies, minor breakdowns of plant and other factors. Clues to the origin of the major causes of variability were immediately given in this way. While these causes were among a long list that had always been recognised, the new procedure led to a greater degree of unanimity of opinion and provided measures of the relative importance of the variability arising from different causes.

While the original inspection scheme was operated by research scientists, it was later simplified and then became part of the normal production duties. The actual measurement of bricks on a simple gauge was undertaken by comparatively unskilled "checkers". At first there was a little doubt to be overcome, but after a short time, and with increasing confidence the entire works' staff began to appreciate the value and simplicity of the scheme. To-day, only three years after the scheme's original inception, the brick size quality control charts are valued throughout the works. The charts, which draw attention to changes in variability and the average size of bricks, now, together with details of pit operation, form the basis of any change in size necessitated by the raw material or the process. Since they also show conformity with B.S. the charts are also of vital interest to the sales staff.

Meanwhile, the necessity for control at an earlier stage in the production process was also being stressed. Quality control charts for the size and weight of "green" bricks, as distinct from the fired product, were introduced, with the consequent immediate reduction in the variability of the final product. These charts now form the basis of a rationalised maintenance programme for the mechanical presses used to make "green" bricks.

The research staff continue to use the small sampling techniques and the control chart methods of presenting results to an increasing extent. Until such techniques were adopted, neither the brickmakers nor the research scientists engaged in the industry had fully appreciated the very big variations that can enter into a highly mechanised mass production process. The considerable increase in efficiency, resulting from reduction in variabilities, has been made possible solely by the adoption of these techniques.

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300 kV Cable for the Aluminum Company of Canada

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In connection with the Kemano-Kitimat transmission scheme of the Aluminum Company of Canada, a contract was placed with Pirelli-General Cable Works, Ltd., for supplying and installing one of the 3-phase oil-filled cable terminations for the overhead line. Transmission is at 300 kV, one of the highest voltages at which industrial cable is at present operating anywhere in the world.

In this article the author deals with the problems of design and manufacture with which the cable engineers were faced.

INTRODUCTION.

A CONSIDERABLE amount of information has already been published concerning the Kemano-Kitimat transmission project of the Aluminum Company of Canada; in consequence the present article deals mainly with the problems presented to the engineers of the Pirelli-General Cable Works who designed and manufactured the cable.

The specification called for high voltage cables capable of conveying a minimum load of 550 amp at 300 kV, 3 phase, from the underground water power station to the commencement of the overhead line, which, in turn, would carry the power to the electrolytic refining plant some 50 miles distant. The cable had to be laid on racks at the side of a tunnel which slopes downwards from the underground transformer chamber, the difference in level between the ends being about 36 ft. The total length of the cable route is 670 yards.

At the time the enquiry was received few cables had ever been constructed for voltages of this order. Oil-filled cables had been supplied for maximum working stresses of 90 kV/cm and some gas pressure cables had been in use at somewhat higher stresses, but for 300 kV working still higher stressing became essential. From previous experience of oil-filled cables, it was decided that a maximum working stress of 120 kV/cm would be feasible provided a dielectric of nearly perfect quality could be ensured.

INSULATION.

With increasing thicknesses of insulation on cables, difficulties are experienced in avoiding wrinkling and creasing of the papers. Defects of this kind reduce the dielectric strength and it was essential that they should be eliminated. Wrinkles occur when the cable, in its undried state, is bent, as, for instance, on a haul-off wheel of a cable-making machine, and then straightened again as it leaves the wheel to go on to the drum. A great improvement can be obtained by substituting a " caterpillar " haul-off for the normal wheel, but for cables of the size under consideration this is not enough. A certain amount of wrinkling and creasing is liable to take place simply by the bending of the cable on to the drum as it leaves the paper lapping machine.

To overcome this it is necessary so to apply the insulating papers in the various layers that the papers will always slip one upon the other when the cable is bent. This presents considerable difficulty and involves a detailed study of the coefficients of friction between layers of papers and the mechanical pressures existing between the layers due to the tension under which these and subsequent layers are applied. It is necessary to apply the papers with the highest tension which can be reached without producing wrinkles, so that as much paper as possible is included in a given insulation thickness. Unless this is done the insulation will be too soft and will be liable to distortion when the cable is bent, or when applying stress control cones in joints and sealing ends.

Trial cables manufactured with paper tensions controlled in accordance with theory demonstrated clearly the improved quality which could be obtained. For whereas, previously, a certain amount of wrinkling and creasing was observed even on 132 kV cables (with insulation thicknesses around $\frac{1}{2}$ in.) cables are now being made having insulation thicknesses of 1 in. and above, which are completely free from such defects.

PROCESSING.

To ensure a high degree of dryness prior to lead sheathing, the cable was provided with an outer screen consisting of semi-conducting carbon paper interlocked with metallised paper. This presented a less impermeable barrier to drying than if metal or metallised paper screening tapes had been used. Initial drying was accomplished in the usual way in a steam-jacketed tank with electrical heating of the conductors. The final evacuation and impregnation of the sheathed cables also followed normal procedure, but longer times than normal were necessary before the control tests showed that the requisite conditions for impregnation had been reached.

The outer end of the cable run, where it leaves the cable tunnel to connect to the overhead line, is sub-

jected, in winter, to extremely low temperatures, a minimum working temperature of −20 deg. C having been specified. The grade of oil generally used would become considerably more viscous at such temperatures and handicap the hydraulic design of the installation. An oil having a viscosity about one-third of the normal but possessing all the necessary electrical qualities was therefore employed.

Details of Cable.

The detailed make-up of the cable is as follows:

Diameter of oil duct	0·75 in.
Size of conductor	0·4 sq. in. (66/·090 in.)
Conductor screen	3 × ·005 in. carbon black paper tapes.
Diameter over conductor screen	1·20 in.
Insulation	Minimum thickness 0·95 in. Made up of 144 paper tapes graded from ·0035 in. at conductor to ·0075 in. in outer layers. Direction of lapping reversed every eight papers.
Outer screen	3 × ·005 in. carbon black paper tapes, the third being interlocked with a metallised paper tape.
Diameter over outer screen	3·12 in.
Lead alloy sheath	0·2 per cent. tin, 0·70 per cent. cadmium (remainder lead). Applied on continuous screw-press.
Impregnation	Low viscosity mineral oil.
Reinforcement	Two silicon bronze reinforcing tapes ·008 in. thickness.
Protective finish	Proofed cloth tape. 2 × ·022 in. rubber tapes. Proofed cloth tape. Two compounded hessian tapes. (All the above applied with waterproof compound at each stage.)
Overall diameter	3·83 in.

Note.—The paper used is made entirely of wood pulp which is washed with distilled water while on the wire of the paper-making machine.

Lapping of the Insulation.

The principal manufacturing problem is the method for ensuring accurate grading of the paper tensions throughout the dielectric. The tensioning devices previously used were inadequate for the precise grading now called for and considerable modifications to the lapping heads throughout the machine were made. Tensions were controlled by passing the paper over a rubber-faced roller incorporating an internal friction brake. To minimise the effect of variation of tension produced by the pad of paper as its diameter becomes smaller, the pads are mounted on ball-bearing spindles with a small adjustable friction pad just sufficient to prevent overrun of the pad as the machine slows up. The tensions are carefully set by means of a hand dynamotor and are checked and adjusted as necessary throughout the run.

It will be clear that it is essential that the whole of the insulation must be applied in a single pass through the machine. The use of thicker papers than usual in the outer (lower stressed) portion of the dielectric was of assistance in achieving this but, even so, further lapping heads had to be added to the machine to enable all the 151 papers (including conductor and external

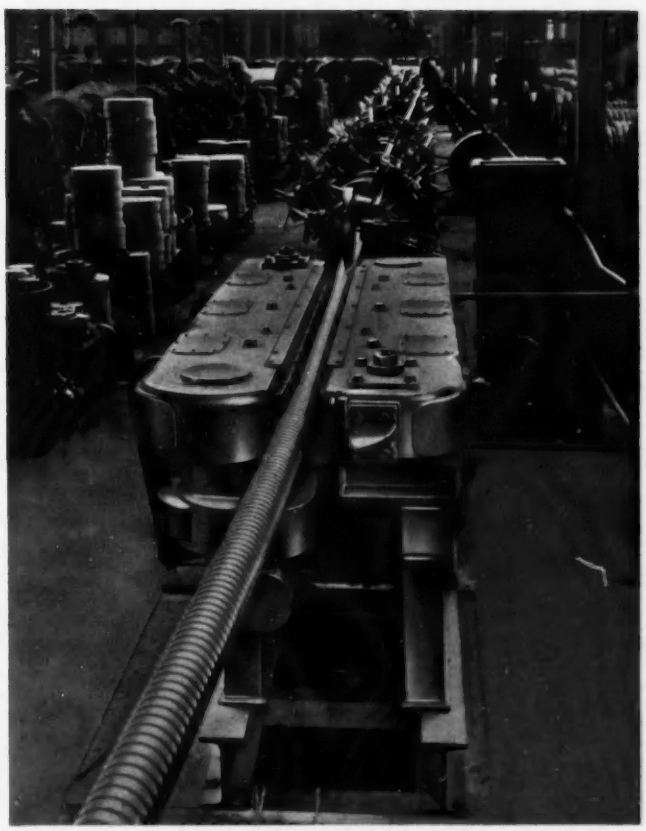

Fig. 1.—Lapping machine, viewed from "caterpillar" haul-off, showing 300 kV cable in course of manufacture.

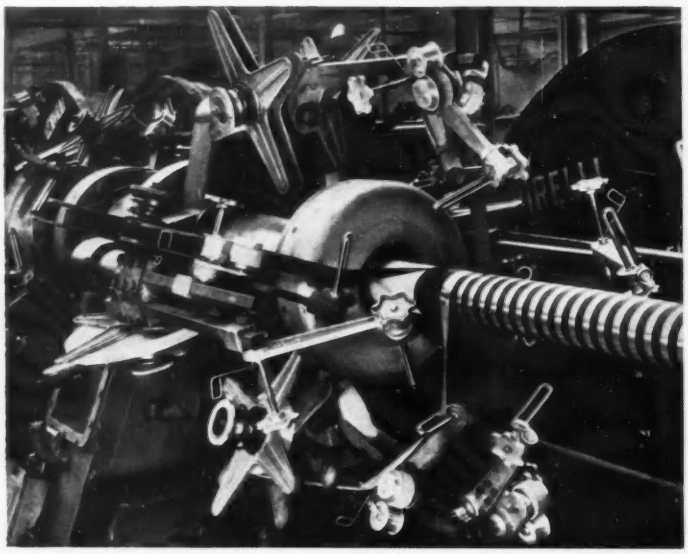

Fig. 2.—Tension control devices shown applying carbon and metallised papers to 300 kV cable.

screening papers) to be applied in one pass. A caterpillar haul-off has been installed in place of the wheel previously used and a new take-off drum stand had to be constructed to accommodate the large metal drums (12 ft. over the flanges) required for cables of this size. The complete machine is shown in fig. 1 and a close-up of one of the tension controlling lapping heads is seen in fig. 2.

Although these tension control devices served their purpose adequately, they required very careful adjustment and supervision to ensure continuously satisfactory results. Consequently a new machine has since been installed having greatly improved tension control devices. This machine was designed by Pirelli, Milan, and manufactured in Milan under their direction. In addition, the whole area in which the paper is stored, cut and lapped on to the cable is being enclosed and the atmosphere automatically conditioned as regards temperature and humidity.

Other Processes.

New drying and impregnating tanks had also to be installed to take the 12 ft. diameter drums and these are seen in fig. 3 which also shows the remainder of the oil-filled cable processing plant in the background. The lead sheathing of the cables was carried out on a continuous screw-type extrusion machine and the reinforcement and anti-corrosive protection were

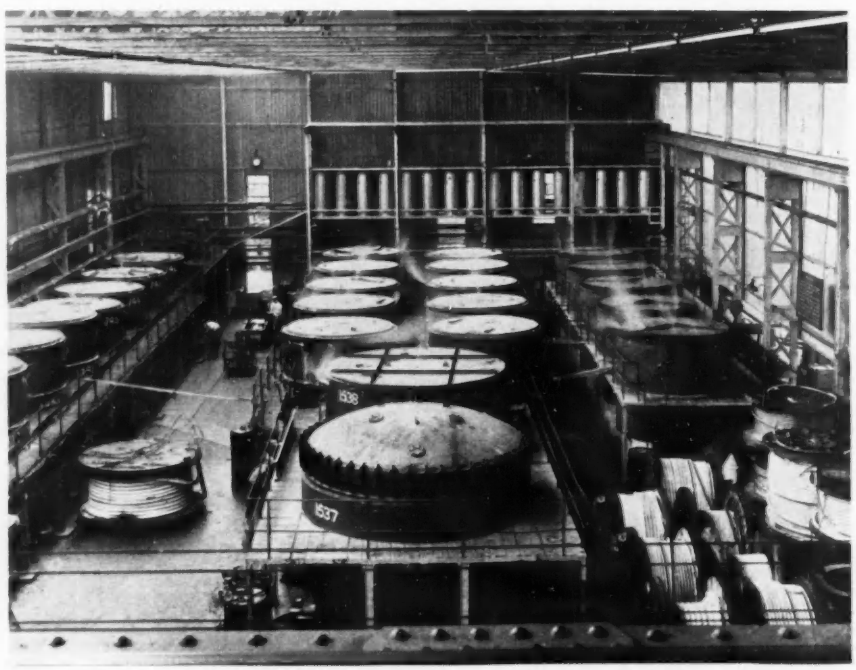

Fig. 3.—View of oil-filled impregnating shop, showing large tanks in foreground.

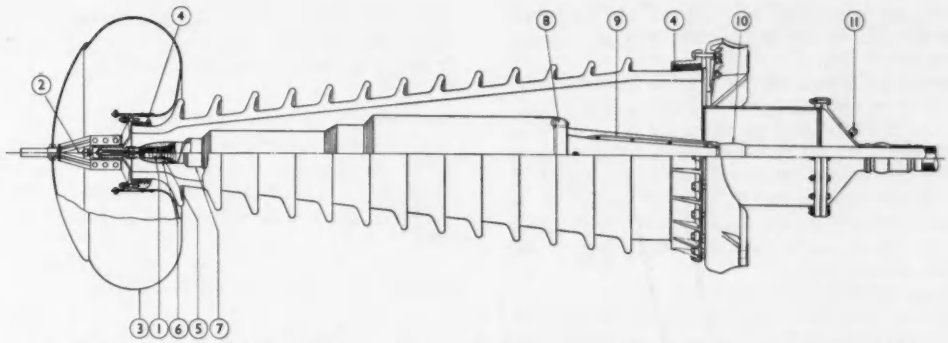

Fig. 4.—Sectional view of 300 kV sealing end. 1—pressed connector ; 2—piston valve ; 3—corona shield ; 4—cement ; 5—silk tape ; 6—paper tape ; 7—paper tubes ; 8—metal stress ring ; 9—metal casing ; 10—wiped joint ; 11—oil feed connection.

applied in a single pass through the armouring machine. Both these processes followed normal practice and presented no new problems.

Accessories.

In spite of the difficulties involved in making satisfactory cables for such high voltages, the results to be expected can be predicted with a fair degree of accuracy. The same cannot be said of the joints and sealing ends where the conditions of stressing are complex and the insulation has to be applied manually and be finally impregnated on site.

The Pirelli Company of Milan were, at this time, working on a large order for 220 kV oil-filled cables and accessories and when the present problem was put to them they immediately undertook the task of modifying and improving these designs to render them suitable for use at 300 kV. In this they were entirely successful.

Sealing Ends.

Fig. 4 shows the design of sealing end as finally evolved. The same sealing end is used both in the underground transformer chamber and for the external connection to the overhead line. It will be noted that the design is conventional in so far that no condenser-type stress control is employed. The porcelains are not resistance glazed and the design can, therefore, be guaranteed to be entirely stable. The success of the design rests in the carefully calculated stress control devices. The sealing ends are mounted on bolted aluminium structures supplied by the customer. The bases are insulated from the structure and the cable sheaths are bonded at the centre of the run only, thus enabling current measuring transformers to be threaded over the cables.

Joints.

The joint design is illustrated in fig. 5 and this again follows the well-established principles used for many years in oil-filled cables. By making the cable in lengths of approximately 230 yards (the longest that could reasonably be handled in the somewhat difficult laying conditions expected on the site) it was possible to reduce the number of joints to two per phase, i.e. six in all. The total length and profile of the tunnel are such that no stop joints are needed.

Oil Feeding Arrangements.

Oil feeding tanks are of standard internal bellows design ; two 225 litre tanks pre-pressurised to 7½ lb.

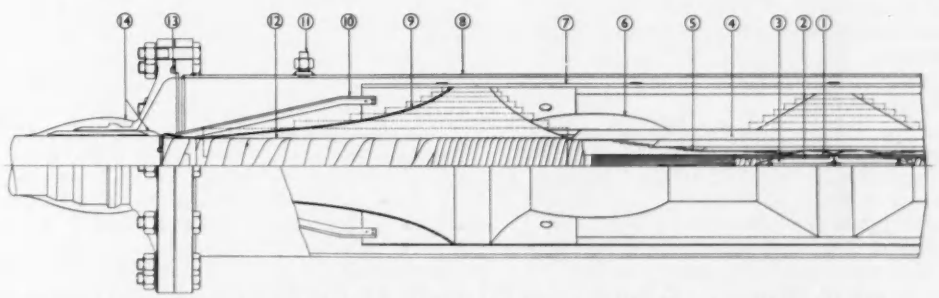

Fig. 5.—Sectional view of 300 kV joint. 1—pressed ferrule ; 2—conductor ; 3—steel inner support ; 4—paper tubes ; 5—cable stepping ; 6—paper tape ; 7—outer screen ; 8—joint casing ; 9—stress cone ; 10—screen support ; 11—connector for evacuating and impregnating ; 12—oiled silk binder ; 13—"O" ring joint ; 14—wiped joint.

per sq. in. are connected to each cable. The feed tanks are located in the transformer chamber at the upper end of the tunnel.

The hydraulic design has to cater for extreme conditions. With the whole cable at extremely low temperature the full load may be suddenly applied. The use of low viscosity oil materially assisted in meeting both these conditions and the maximum transient pressure cannot exceed 40 lb. per sq. in. This is somewhat less than the maximum static pressure which is 50 lb. per sq. in. in the cable and 44 lb. per sq. in. in the lower sealing end.

Oil leakage protection is provided by a triple unit differential oil pressure indicating switch situated in the transformer chamber and cross connected in the usual way.

Type Test Specification.

The acceptance type tests required by the customer to prove the suitability of the cable for its purpose were as given below:

(*a*) *All* cable for electrical type tests were to be subjected prior to assembly for testing to four consecutive bends in one direction followed by four bends in the reverse direction round a drum of 130 in. diameter.

(*b*) An assembly consisting of a length of cable, after bending as above, together with a joint and two sealing ends was required to withstand 350 kV r.m.s. for 24 hours. The voltage was then to be raised in steps of 25 kV at one minute intervals up to 425 kV r.m.s. and maintained at this voltage for at least two hours.

(*c*) A similar assembly consisting of a joint and two sealing ends to be submitted to 10 positive impulses at 1,050 kV (peak) followed by 10 negative impulses at 1,050 kV (peak). This represents a maximum stress at peak of 725 kV/cm.

(*d*) A 30-yard length of cable, previously subjected to bending as above, with one joint and two sealing ends to be subjected to 1·33 times working voltage (i.e. 232 kV to earth) continuously and twenty current loading cycles to be applied up to the maximum working conductor temperature of 80 deg. C. Power factor/voltage runs to be applied at maximum and minimum temperature of each heat cycle.

(*e*) All assemblies to be dismantled after the tests and visually examined for any signs of commencement of breakdown.

Type Test Results.

As this was the first contract for cables of this voltage ever made in the factory, the opportunity was taken of extending the tests well beyond those actually specified so as to gain some knowledge of the margin of safety. The results are summarised below and it will be seen that all components gave a highly satisfactory performance even when tested at stresses well above specification and at conductor temperatures higher than those for which the installation was designed.

Four separate assemblies were tested, each assembly consisting of a length of cable which had previously been subjected to bending in accordance with (*a*) above, two sealing ends and a joint. A typical type testing assembly is illustrated in fig. 6.

First Assembly—A.C. Tests.

(*a*) Beginning at 200 kV r.m.s., the voltage was increased in steps to 475 kV where it was held for 4 hours. A test of 15 minutes at 500 kV was finally applied. These tests were made at ambient temperature.

(*b*) A.C. tests at elevated temperatures (conductor heating) were next applied as follows:

Conductor temp.	kV r.m.s.	Duration
60-65 deg. C.	200, 250, 300	12 hours each
„	350	24 „
70-75 deg. C.	200, 250, 300	12 hours each
„	350	24 „
80-85 deg. C.	200	12 hours
„	250, 300, 350	12 „ each
„	425	30 „
100-105 deg. C.	350	24 hours
„	425	10 „

Breakdown occurred at the junction between one of the joint stress cones and the cable sheath. Insulation over the ferrule of the joint was also found to be slightly charred, indicating possibly the start of a thermal failure. The remainder of the joint, all the cable and both sealing ends showed no signs of impending failure. This assembly thus fully satisfied the A.C. test specified with a large margin.

Second Assembly—Impulse and A.C. Tests at Ambient Temperature.

(*a*) After the assembly had passed the specified impulse test of 10 positive and 10 negative impulses, the voltage was increased in steps up to 1,150 kV (peak), when external flashovers occurred, a total of 80 impulses being applied.

(*b*) The following A.C. tests were then applied:

kV r.m.s.	Duration
350, 375, 400	15 minutes each
425	12 hours
450	1 hour

(*c*) A further 40 impulses at 1,135 kV (peak), chosen to avoid further flashovers, were then applied, followed by 40 more at 1,050 kV (peak).

(*d*) Another A.C. test of 425 kV r.m.s. for 4 hours.

(*e*) To enable impulses of still higher voltage to be applied without external flashover, the corona shields on the sealing ends were temporarily modified and impulses, both positive and negative, were applied up to 1,250 kV (peak) at which voltage external flashover again caused testing to be discontinued.

This test assembly, therefore, in addition to complying fully with A.C. test requirements withstood a total of 260 impulses between 1,050 kV (specified test) and 1,250 kV. Visual examination after the tests showed no signs of deterioration in cable, sealing ends or joint.

THIRD ASSEMBLY—IMPULSE TESTS AT AMBIENT AND ELEVATED TEMPERATURES.

(*a*) The specified impulse test of 10 positive and 10 negative impulses was first applied at ambient temperature.

(*b*) This was followed by A.C. tests at ambient temperature of 350 kV r.m.s. for 24 hours and 425 kV r.m.s. for 2 hours.

(*c*) Further impulse tests at ambient temperature commencing at 1,050 kV (peak) and rising to 1,250 kV (peak), a total of 60 more impulses was then applied.

(*d*) The whole cable was next heated by means of external heater wires, combined with suitable lagging and the following series of impulses applied:

kV (peak)	Polarity to earth	No. of impulses	Cable temperature
1050	Negative	10	62 deg. C. Falling to 46 deg. C.
1050	Positive	10	
1050	Negative	10	89.5 deg. C. Falling to 78.5 deg. C.
1050	Positive	10	
1150	Negative	10	84 deg. C. Falling to 68 deg. C.
1035	Positive	1	
1100	Positive	1*	
	Total	52	

* Breakdown occurred.

The breakdown occurred in the joint beginning at the ferrule and continuing along the stepped insulation to the stress cone. There were no signs of impending failure in the cable itself or in either of the sealing ends.

FOURTH ASSEMBLY—LOAD CYCLE TESTS.

This test was carried out in the normal way with 232 kV to earth applied to the conductor. Twenty load cycles were applied by heating the conductor electrically to temperatures ranging between 81 deg. C. and 87 deg. C., the average being 84·5 deg. C.

As might be expected from the results of the previous tests, the cable remained entirely stable and, on examination after the test, all components were in perfect condition.

ROUTINE TESTS.

The routine test to be applied to every length of cable was originally specified as 300 kV for 15 minutes. Due, however, to some trouble experienced with one of the testing transformers at this time it was not possible to reach this voltage on a full production length of cable (230 yards). In view, however, of the excellent margin of safety demonstrated by the type tests, the customer agreed to accept a test of 250 kV for 30 minutes. Power factor/voltage measurements were made both before and after the high-voltage test and any manufacturing defects would be shown by changes in the power factor/voltage relationship. The specified maximum power factor figures were:

87 kV	0·0028
174 kV	0·0028
261 kV	0·00305
348 kV	0·0033

and all the lengths manufactured fell comfortably within these limits.

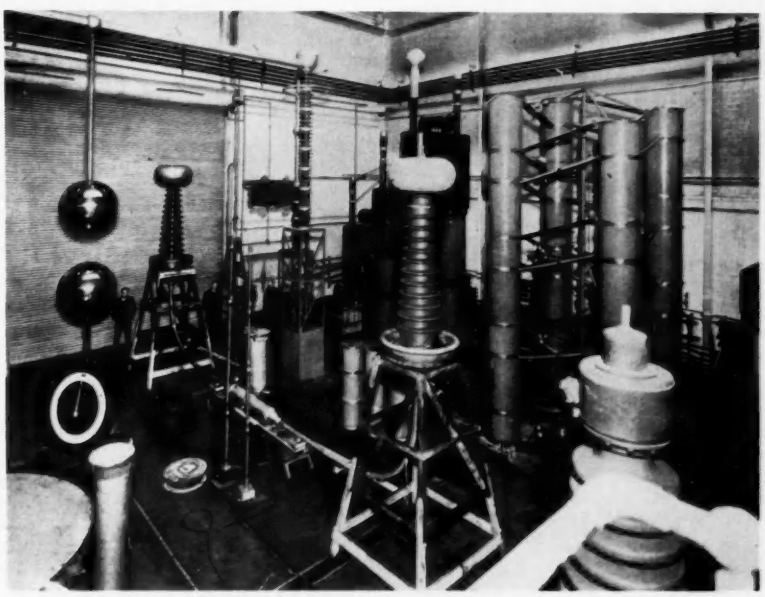

Fig. 6.—Typical impulse test assembly of 300 kV oil-filled cable in the G.E.C. High Voltage Laboratory at Witton.

Plastics—A Decade of Progress

By R. C. CHIRNSIDE, F.R.I.C.
Research Laboratories.

INTRODUCTION.

TOWARDS the end of the war an article on the Chemistry of Plastics was published in this Journal.* At that time there was some extravagant talk of the coming of a "Plastics Age"! It is therefore pertinent to re-examine the situation after ten years; has the "Plastics Age" arrived, is it imminent, will it, indeed, ever come?

That there is a need for such a reassessment is clear because of the bewildering choice of materials that now confronts the designer or the engineer when he wishes to consider the use of plastics. The confusion arises primarily because the name—plastics—comprises such a heterogeneous collection of materials. The members of the traditional groups of metals and alloys, although perhaps as numerous, have always been readily identifiable because they fall into a few main classes, the properties of each of the classes being quite distinct and the individual members of each class differing only in degree from the other members. The names, too, brass, bronze, aluminium, white metal, established traditionally, continue to serve for any new additions to the range. By comparison, the situation with regard to plastics is confused. Only a few naturally occurring materials such as cellulose and rubber are plastics, and natural rubber is not conventionally included under this name. The remainder are what the layman recognises as chemicals and to give them their chemical name would usually serve only to add to the confusion. Some few indeed are known by their correct chemical names; with others, the material will be known by one or more trade names, according to the number of manufacturers involved, and the user has to remember and identify these different names used to describe essentially similar materials. Unfortunately, the number of such names seems to increase with every number of the trade journals. The non-specialist has also to remember that, in chemical nomenclature, there is the well-established practice of using a "trivial" name to describe a substance, the correct chemical name for which would be too long or cumbrous for everyday use.

Unlike the metals and alloys the many plastics materials have so many properties in common that this is yet another factor in the difficulties of assessment that face the potential user.

* "The Chemistry of Plastics," by R. C. CHIRNSIDE, F.R.I.C., *G.E.C. Journal*, Vol. XIII, No. 2, August, 1944, pp. 74-89.

RAW MATERIALS.

We may say, almost without qualification, that the raw material of plastics is carbon, and carbon has to be made available in one form or another from some natural source. Cellulose, a natural source of carbon, was the raw material of the earliest plastic—celluloid

Fig. 1.—Fabrics made water-repellent with silicone finishes

(essentially cellulose nitrate). The many other plastics based on cellulose, including pure, chemically regenerated cellulose itself in the form of "Cellophane", are based on a replenishable raw material.

For the others, coal is the obvious indigenous source of carbon and it is as true now as it was ten years ago that—"our coal should be made to yield much larger amounts of valuable chemicals. We cannot afford indefinitely to put so much of our national wealth into the air in smoke". There is now some official concern to limit the amount of smoke produced, but for quite a different reason. Nor have the ordinary demands on the coal that has been mined

in any of the last ten years left any over for use as a source of chemicals. Developments of much greater significance to the chemical industry have taken place, however, and their full effect has not yet been felt. Three large petroleum refineries have been brought into operation in this country and joint organisations of the largest oil and chemical companies have been created to develop the " petrochemical " industry. The political happenings in Persia and the exploitation of the rich oil supplies of Kuwait have not been without influence in this situation and we are at present in the early stages of a great expansion of our chemical industry.

Calcium carbide too is now in more plentiful supply, and from this acetylene, one of the basic raw materials of the plastics industry, is produced, and so too, indirectly, is melamine, used in the preparation of the melamine-formaldehyde resins.

As a result of the changed position in raw material resources here and elsewhere and of other changes in our economy, we may ask what plastic materials have now become available that were new ten years ago, and also what has been developed since that time. In any list we must include the silicones, " Terylene ", the fluorocarbons, the epoxy and the polyester resins. There are in addition developments and modifications of many of the older plastics or of those that were available in a restricted sense at the end of the war.

THE NEWER PLASTICS.

We may consider under this heading, briefly, the nature, outstanding properties and applications of each of the newer types of plastic.

THE SILICONES.

The name silicone is applied to a class of material of which the individual members may be oils, greases, resins or rubbers —more properly called elastomers.

This class of compound differs uniquely from all the others in that its members are built on a molecular backbone of silicon rather than carbon. The silicones are indeed chemical hybrids, derived as they are from inorganic and organic materials. For the purpose of this article they may be defined as synthetic compounds containing the elements silicon and oxygen, together with what the chemist calls organic groups, e.g. methyl, CH_2, ethyl, C_2H_5, or phenyl C_6H_5, groups, comprised only of carbon and hydrogen. Just as quartz or silica sand, SiO_2, which has a very high melting point, is made more tractable by the incorporation of soda and lime to form a lower melting point glass, so, if the analogy is not pushed too far, does the incorporation of these organic groups into a network of oxygen-silicon-oxygen, O-Si-O, result in the materials now produced commercially as silicones.

In 1945 these materials had been in manufacture in the U.S.A. for only two years and the products had been used almost exclusively for military purposes. In the last ten years the production has greatly increased and the uses have multiplied. The silicones are now made in this country by one chemical company and will be available shortly from another.

All the silicones exhibit two outstanding general properties, heat resistance and water repellency. The different types of silicone offer, in addition, some unique properties. The rubbers are no more " rubbery " than the natural or synthetic rubbers at ordinary temperatures, but they remain " rubbery " at −50 deg. F. and at +500 deg. F., temperatures at which the other rubbers, natural and synthetic, would be either hard, brittle solids, or charred, sticky masses. They have also a higher thermal conductivity than natural rubber and are unaffected by ultra violet radiation. An obvious application is as a covering on lead wires where the insulation is likely to be exposed to high temperatures. More recently small power transformers have been covered with silicone rubber.

The viscosity of the silicone greases and of the fluids remains constant over a very wide range of temperature. The compressibility of the oils is high compared with that of other hydraulic fluids and they have been used in damping devices. They have also been incorporated in " polishes " for motor cars or for furniture. Used in conjunction with a good wax they enable a high-gloss, water-repellent surface to be obtained with much less effort than when the wax is used alone. A solution of one of the fluids is used for treating masonry and brickwork which is exposed to driving rain. The special water repellency prevents

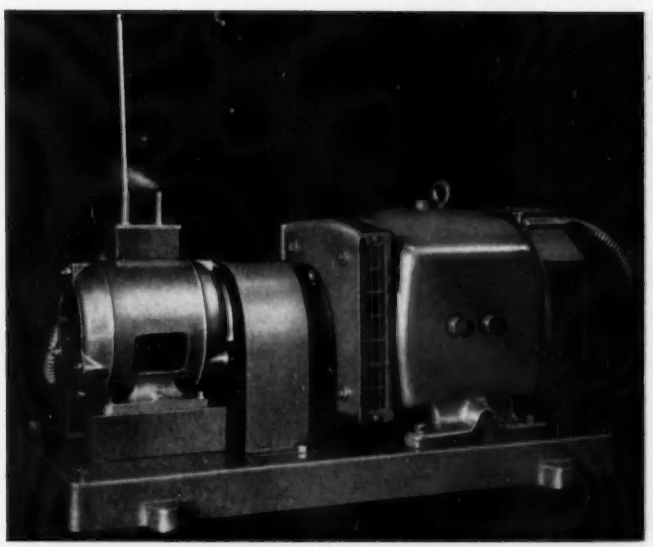

Fig. 2.—Motor-generator set with silicone-insulated motor. The motor is running with a pan of boiling water on top of it.

the penetration of moisture along capillary channels. Glass surfaces can also be treated to give a water-repellent surface.

The resins form the basis of new types of electrical insulation. Used as a varnish impregnant, or by incorporation with glass or asbestos fibre or cloth, or with glass-mica combinations, they offer a complete high-temperature range of insulating materials, and one in which the special virtues of glass may be exploited. A new "Class H" insulation with a permissible temperature rise of 180 deg. C. is now accepted by the A.I.E.E. and there is some likelihood of similar specifications being accepted in this country.

Although there are very good electrical reasons for restricting the temperature rise in a motor, the useful rise that silicone insulation will allow means that some reduction in frame size can be achieved by suitable re-design; the extra safety factor is, of course, considerable. As early as 1946, the Witton Engineering Works of the G.E.C. constructed a motor for demonstration purposes embodying an all-silicone insulation. This was operated for part of its life at a temperature high enough to boil a kettle of water standing on top of the motor! In spite of several immersions in tap water and in sea water the motor continued to run for some thousands of hours. An open circuit finally developed in the end winding through oxidation of the copper conductors. This oxidation had evidently caused a local increase in resistance and the temperature must have risen sufficiently to cause fusion of the copper. Since that time a number of motors has been made for special applications.

The water-repellency properties of the insulation suggest useful applications, for example, in marine work, in chemical plants and in coal mines. The special heat stability of the insulation is of value in traction motors and in exposed positions, for example, on hot rolling mills and other metallurgical plant.

Among the miscellaneous other uses of the silicones may be mentioned: mould release agents for rubber, plastics, some cast metals, some ceramics and for the treatment of baking tins. Textiles and leather can be treated to give water repellency. One of the silicones is an effective antifoam agent for oils, hydraulic fluids, tars, impregnating varnishes. In appropriate circumstances the oils or compressed greases have special merits as lubricants.

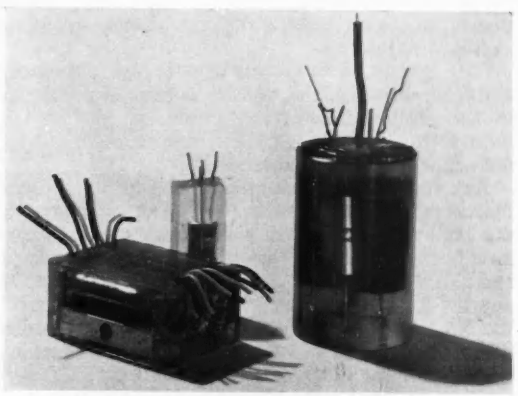

Fig. 4.—Electrical components cast in Epikote resins. [A Shell photograph.]

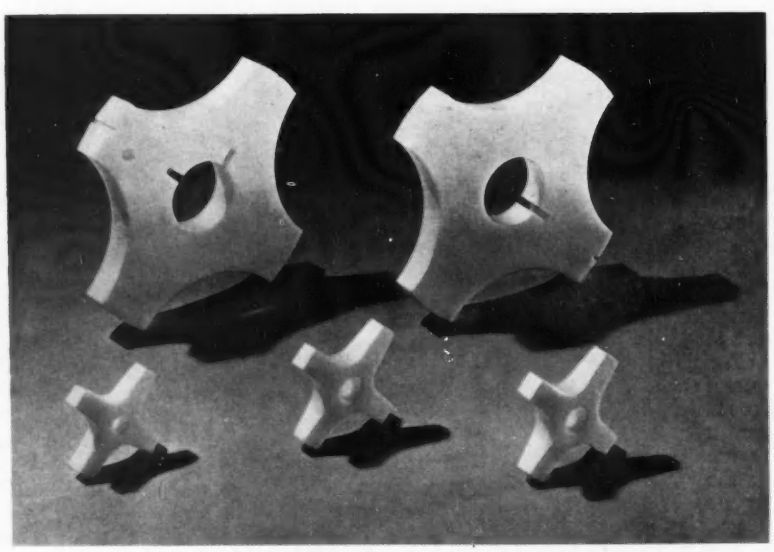

Fig. 3.—Kent polytetrafluorethylene mouldings for radio transmitter components. [Courtesy "British Plastics".]

FLUOROCARBONS.

Scientific and technological developments directed to one objective invariably open up new and correlated developments in other directions. The element fluorine, previously almost a chemical curiosity, was made during the war in large quantities and much of it was used in processes connected with atomic energy. The availability of fluorine in greater quantities stimulated the preparation on a larger scale of a number of new compounds, and also of some of the older compounds such as the refrigerant dichlorodifluoromethane, CCl_2F_2, better known under the trade names "Freon" or "Arcton." From one of this group the substance polytetrafluoroethylene (C_2F_4), known as P.T.F.E., or under the

trade names " Teflon," or " Fluon " can be prepared. This substance is a new addition to the range of plastics, and, like the silicones, offers improved resistance to heat over all the other members. It does not undergo excessive thermal degradation until a temperature of 450 deg. C. is reached and reasonable mechanical properties are retained up to temperatures of 200 deg.-250 deg. C. The material is also extremely inert to chemical attack and no solvent has been found for it. It has an extremely low coefficient of friction both against itself and also against metal surfaces. Indeed, it has been proposed recently to use it on skis with an expected gain in speed of 50 per cent.

Its virtues bring their own limitation, for the material does not flow or flux in the normally accepted sense and methods of fabrication which depend on these properties cannot be used. The material in powder form has to be compressed to give a pre-form which, when raised above the transition temperature of 327 deg. C., retains its shape without the application of pressure. Another promising technique is in the use of concentrated dispersions of the powder. These can be used for enamelling wire or for coating glass fibre cloth.

P.T.F.E. is finding applications where heat resistance, combined with very good electrical characteristics and chemical resistance, is required. Moulded electrical and radio components have been developed to work at high ambient temperature and humidity. In chemical plant it is invaluable for gaskets, valves and seals of various kinds.

The bad flow characteristics of P.T.F.E. have led to a search for other more tractable fluorine-containing compounds. The mixed chloro-fluoro compound polymonochlorotrifluoroethylene $(C_2ClF_3)_n$, known in the U.S. under the trade names " Fluothene " and " Kel-F ", has improved flow characteristics and can be injection moulded and extruded. Chemical resistance is good, temperature resistance is a little lower than P.T.F.E.

Fluorine chemistry is still in its early stages of development and some interesting possibilities are believed to lie in the fields of fluoro-lubricants and fluoro-rubbers.

Epoxy Resins.

This new class of compound, first manufactured about 1947 and an outcome of " petrochemical " developments, has already been found to have a variety of useful applications. The typical compound of this class is the polymer of a condensation product of the two chemicals, diphenylolpropane and epichlorhydrin.

The resins can be " cured " with a variety of hardening agents of both amine and acid types, or they can be esterified with fatty acids to produce " vehicles " for varnishes. They may also be " cross-linked " with phenolic resins or amino resins to give stoving finishes. Surface coatings for metals formulated from epoxy resins have shown outstanding protection against corrosion in some circumstances, for example, they are particularly resistant to alkalis and detergents and have been used on domestic appliances.

An application of special interest to the electrical industry is the use of epoxy resins as " potting " or casting compounds. In addition to their good resistance to thermal and mechanical shock, their outstanding property is good adhesion to metal inserts.

As casting resins they have found a special application in the manufacture of press tools for the light metal industries.

Adhesives, both hot and cold, based on the epoxy resins have outstanding qualities for bonding metal, glass, ceramics, plastics, rubber or wood. The aircraft industry has made great use of these adhesives

Fig. 5.—Martin car with body formed by Martin Plastics Ltd. from glass fibres bonded with Bakelite polyester resins.

Fig. 6.—Crash helmet made by Slazengers Limited of glass fibre reinforced Cellobond polyester resin.
[Courtesy "British Plastics".]

for bonding metal in place of older techniques of fabrication of structures.

POLYESTERS.

Chemically the polyesters are condensation products of di- or poly-basic acids with di- or polyhydric alcohols. The so-called unsaturated polyesters are based on unsaturated di-basic acids such as maleic or fumaric acid. They can be cured by polymerisation with styrene.

The special interest derives from the unique properties of the glass-fibre, low pressure laminates. They offer to the engineer a new material of construction, and car bodies and boats, for example, have been made in which the high rigidity, toughness and high impact strength of these materials are utilised.

"TERYLENE."

"Terylene," a polyester worthy of separate mention, is formed from ethylene glycol and terephthalic acid. It is best known through its use as a textile fibre and is sold under the trade mark "Terylene polyester fibre." Discovered in this country, large scale production was initiated first in the U.S.A. where the fibre was marketed under the trade name "Dacron." More recently it has been made available there in fibre or sheet form under the trade name "Mylar." Plant for the large scale production of this unique material is now nearing completion in this country.

Any plastic having useful, or, as with "Terylene", outstanding properties as a textile fibre, gains thereby the commercial momentum which eventually justifies its production for other more specialised, but extremely useful, applications. "Terylene", although a thermoplastic, resembles Nylon in that it has a high softening point, approximately 270 deg. C. A maximum operating temperature of 150 deg. C. is recommended.

In film form it promises to be of outstanding importance to the electrical industry. The published information about "Mylar" shows it to have low water absorption, unusually high tensile strength (23,500 lb. per sq. in.), outstanding dielectric strength (4,000 volts per mil), high insulation resistance (10,000 megohm mfd at 25 deg. C.), a power factor of 0·003 at 50 cycles and a dielectric constant above 3·0 at most frequencies. It is available in the U.S.A. in film thicknesses ranging from 0·00025 in. to 0·0075 in., and is finding use as a dielectric in capacitors, in motor and transformer insulation, and as a base for recording tape.

NYLON.

Originally available only in filamentary form, Nylon, or more correctly the Nylon group of plastics, for there are several varieties, can now be moulded and extruded. Coil-forms were among the first items to be moulded of nylon. It has also been found particularly suitable for gears and for bearing cages. Many parts of textile machinery, for example, are now made of moulded Nylon because of its high abrasion resistance and low coefficient of friction, and because it requires no lubricants for light loads at high speeds, or moderate loads at lower speeds.

Nylon coatings may be applied to electrical wire as an insulation or as a protective jacket over an insulation of polythene, rubber or vinyl compounds.

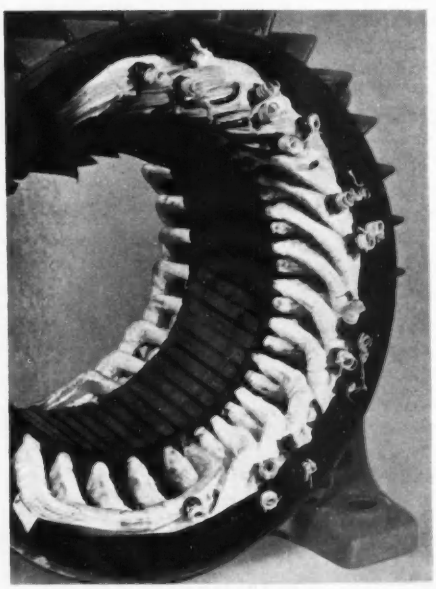

Fig. 7.—"Terylene" insulating material in use on the stator coils of an electric motor.

The high tensile strength associated with Nylon filaments cannot be achieved in moulded articles, for in this form orientation of the molecules cannot be obtained as it is by cold drawing of the filamentary form.

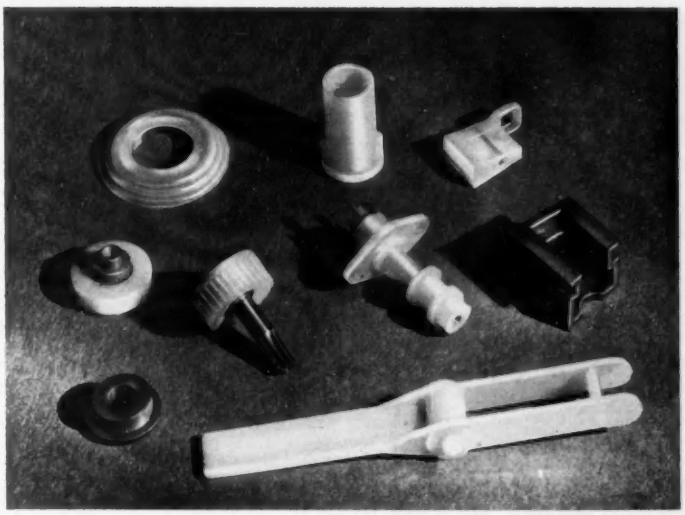

Fig. 8.—A selection of Nylon mouldings, including gears, bearings and bushes.

The Vinyl Polymers and Co-polymers

P.V.C. Polymers.

Although not new, in the last ten years P.V.C. (polyvinyl chloride), used during the war as a substitute for rubber, has established itself on its intrinsic merits. Improvements in the use of plasticisers and stabilisers have taken place, but what is perhaps more important, rigid un-plasticised P.V.C. has become available.

Rigid P.V.C. can be formed by extrusion, by compression and injection moulding and by calendering. Final fabrication can be accomplished by deep drawing, welding, drilling, sawing and threading.

The good resistance of P.V.C. to many chemicals, to moisture, and to abrasion has led to its use for piping, filters, exhaust systems, guttering and spouting.

The plasticised material continues to be used in the wire and cable field, no longer as a substitute for rubber but for those applications where it is superior in service.

Liquid dispersions of the vinyl polymers can be spread on cloth or other supporting agent and floor coverings in tile or sheet are also available. The ability to take a variety of colours adds to the appeal of the materials.

Vinyl Co-polymers.

Co-polymers of vinyl chloride and vinyl acetate have been used particularly for solution coatings, but they are also supplied as powders, sheets, rods and tubes.

The co-polymers of vinyl chloride and vinylidene chloride (of which that made under the trade name "Saran" is an example) give an extremely useful range of products. Films of this material have an exceptionally low rate of transmission of water vapour. They are easily heat-sealed, non-flammable and have good chemical resistance. Extruded filaments are used in weaving durable fabrics very resistant to abrasion.

Polyvinyl alcohol can be reacted chemically to give vinyl acetate, vinyl butyral or vinyl formal, each of which has specific virtues in the field of adhesives, impregnants, coatings and films. Vinyl butyral, for example, has been used as a laminate for safety glass.

An important recent development in the field of surface coatings lies in the pretreatment of metals with "wash primers" based on vinyl butyral resins. Applied in an extremely thin film, they provide an excellent bond for subsequent coats.

Vinyl formal resins are used as coatings for enamelled wire, often in combination with cresylic or phenolic resins, and have largely displaced the old oleo-resinous coatings.

The vinyl polymers are certainly among the most useful and important of all the plastics. From a few thousand tons per annum in 1939 the world production of P.V.C. alone has now risen to 350,000 tons per annum, and it is predicted that this will rise to 500,000 tons by 1958.

"Orlon."

It is inevitable that with the rapid development of synthetic organic plastic materials their chemical identity will become obscured by the "trivial" or trade names by which they become known. The trade name "Orlon" does not of itself indicate that this material can also be regarded as a vinyl polymer—a polymer of acrylonitrile, or of vinyl cyanide—or alternatively as one of the acrylic class of resins. "Vinyon N" is the trade name of a co-polymer of vinyl chloride and vinyl cyanide. Both are products of American chemical companies.

Fig. 9.—Application of P.V.C. to upholstery and floor coverings. [Courtesy British Geon Ltd.]

The outstanding property of "Orlon" is its resistance to light and even to outdoor exposure. Laminates, varnished fabrics and silicone-coated fabrics are mentioned as likely applications.

Co-polymers of butadiene with acrylonitrile form the basis of one of the varieties of synthetic rubber.

THE OLDER PLASTICS.

Most plastics belong to the class of material known to the chemist as "high polymers". In simple terms, this means that the substances contain very large molecules, the molecules being built up on a repeating chain or network of identical units of the "monomer". The high polymer, polyethylene, for example, is known to be a long chain of repeating groups of the monomer ethylene, "$CH_2=CH_2$".

Fig. 10.—Heavy duty junction box for the Ministry of Supply, moulded from chopped cotton fabric filled phenolic material to stand up to the roughest outdoor applications.

The body of knowledge that has grown up in connection with these "high polymers" or "macromolecules" is of direct application to some of the older plastics. Cellulose itself is a natural high polymer comprising as it does a long chain built on the repeating unit or building brick of a molecule of glucose. Had it been a synthetic high polymer it might well have been called "polyglucose."

The growth in knowledge in the field of high polymer chemistry has not been without influence on the older type of plastic, and in the light of this it is worth surveying briefly the present situation with regard to some of the developments connected with these older materials.

CELLULOSE.

The world production of plastic based on cellulose has jumped steeply and is now of the order of 200 million pounds a year.

Cellulose nitrate (nitrocellulose)—in the form of celluloid—the first of the plastics, continues to be used in large quantities, especially in lacquers.

Cellulose acetate and the acetate-butyrate co-polymer are also manufactured in large quantities in the form of sheet, rod and tube. They are particularly suited to injection moulding processes. The use of acetate silk (cellulose acetate) is, of course, maintained at a high level despite the introduction of Nylon and "Terylene."

Cellulose tri-acetate is a newer product and finds a use where lower water absorption and high strengths are required.

Cellulose itself, i.e. chemically regenerated cellulose — "Cellophane" — is well known as a packaging material and it may be surface treated so as to make it more nearly impervious to moisture. Where better protection against moisture is required, P.V.C., polyvinylidene co-polymer, or polyethylene film may have to be used.

Among the newer cellulose plastics that are used in considerable quantities are methyl cellulose, carboxy-methyl cellulose, and ethyl cellulose.

The first two are water soluble and give highly viscous, stable solutions. They are commonly used as thickening agents and emulsifying agents for oil-in-water solutions, coatings for carton board, as a binding agent for ceramics, in toilet preparations and in a number of other applications in place of natural gums such as tragacanth.

Ethyl cellulose is the lightest of the celluloses; with a density of 1·1 it is of value where lightness with maximum strength is required. It can be compression, injection or extrusion moulded. Lacquers for brushing, spraying or dipping can be formulated and

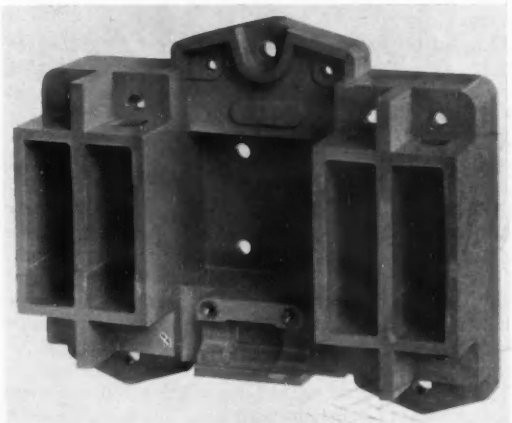

Fig. 11.—Contactor base moulded in Alkyd compound.

articles, for example tools, can be dipped in the hot melt for temporary protection, the coating being subsequently stripped. It can be used as a sealing or potting compound with a good degree of electrical resistance.

PHENOLIC RESINS.

The phenolic types of resin are the oldest and most common of the thermosetting type and continue to be produced for use in moulding powders, bonding and adhesive resins for laminating plywood, abrasives, brake linings, thermal insulation (with fibreglass), varnish and paint resins.

By " cross-linkage " with epoxy resins a new range of materials has been produced of outstanding flexibility and toughness, together with a high degree of chemical resistance.

UREA AND MELAMINE RESINS.

The urea and the melamine resins, also thermosetting, are used for moulding, textile and paper treatment, bonding and adhesive resins, and for protective coatings.

Melamine resins have particularly good temperature resistance and outstanding resistance to electrical " tracking " and arcing.

ALKYD RESINS.

The alkyd resins, typified by the product of condensation of glycerol and phthalic anhydride, are largely used in the modern stove enamels or " synthetics." They may be combined with natural resins or with other synthetic resins of different type. They are also blended chemically with drying oils to give air drying surface coatings of high quality.

More recently, alkyds have been developed by the Plaskon Company in the U.S.A. for moulding purposes, more especially in the electrical industry. The water absorption is low and resistance to tracking is good. They have a low electrical loss factor, good heat resistance and good mechanical properties. The ability to use exceptionally high moulding speeds makes these resins attractive for many electrical applications.

Reinforced with fibreglass they attain very high strengths and have many applications where strength and good electrical characteristics are important.

Because of the soft-flow, low pressure characteristics of the alkyds, many mouldings involving delicate inserts have been more readily achieved with these materials than with any other thermosetting plastics. They are now being produced in this country.

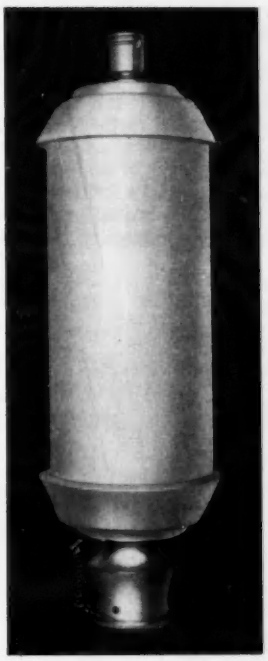

Fig. 13.—Side road fluorescent lantern with opal " Perspex " cylindrical enclosure.

POLYSTYRENE.

Polystyrene is a rigid thermoplastic, well suited for injection and extrusion moulding. It is of low specific gravity, and of crystal clarity ; it has good electrical properties and good resistance to water.

Although polystyrene has been in widespread use for many years there have been recent improvements and modifications directed to correct some of its shortcomings. The modifications have been directed to three main features, to give an improvement of 10 deg.-30 deg. F. in heat distortion temperature, greater resistance to chemical and solvent attack, and higher impact strength.

Improvements have been obtained in general by co-polymerising styrene with other monomers such as acrylonitrile or butadiene or by mechanically mixing polystyrene with other polymers. The higher temperature formulations require higher

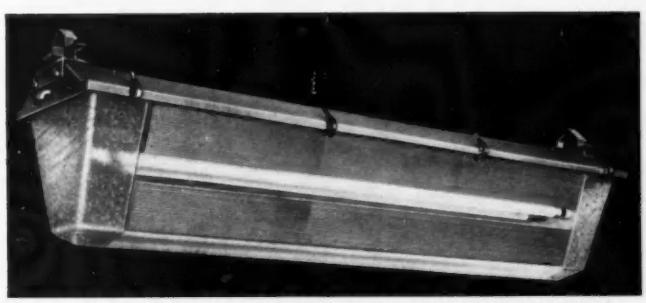

Fig. 12.—Three-Eighty lantern for fluorescent street lighting with the tubes enclosed by a vee-shaped " bath " of unplasticised " Perspex."

moulding temperatures and pressures and residual strain is removed by annealing. Articles of heat resistant polystyrene may be safely treated in boiling water, for example, for sterilisation.

This material may be attractively coloured and its high impact strength has led to an extended use of these materials, for example, as interior fittings for refrigerators. Decoration by metallising or by back painting, or other techniques, lends attraction to some of these articles.

One defect of the general purpose polystyrene is its tendency to become yellow when exposed for long periods to direct sunlight or to some forms of indoor lighting. Light-stabilised varieties are now available which enable the material to be used for light diffusing panels and for other applications in the lighting field, but this type is limited to the clear, translucent and opaque white varieties of the material.

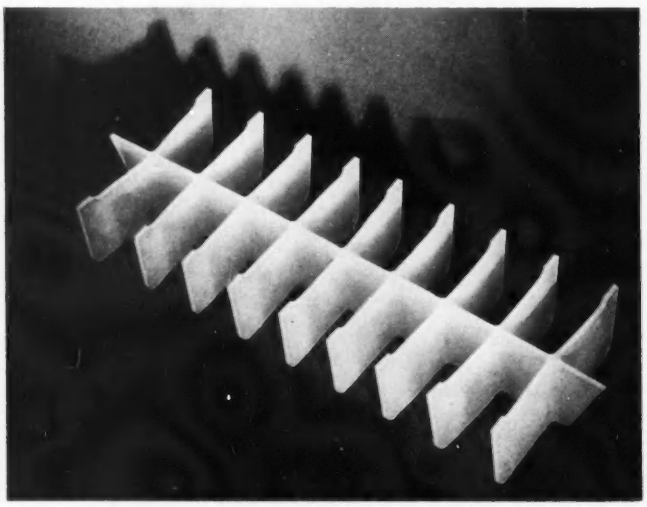

Fig. 14.—An ice cube divider in polythene which maintains its flexibility well below freezing point.

Polystyrene readily acquires a static charge and the readiness with which it picks up dust is one of the major disadvantages of its use for some purposes. Anti-staticising agents are now available : these are usually dilute solutions of surface active agents which have to be applied externally.

The Acrylics.

The " acrylics," of which the methacrylate resins are the best known, are thermoplastic. They have been available for many years in this country in two forms, as " Perspex " acrylic sheet, or as " Diakon " moulding powder, suitable for compression, injection or extrusion moulding.

The excellent optical qualities, ease of shaping and machining, low water absorption, ability to take attractive colours, and, in " opal " form, to diffuse light, have finally established this as one of the best known plastic materials.

Progress has been connected more with an extension of the use of the most important member of the group, methyl methacrylate, rather than with the development of new acrylic resins. The optical qualities of the material, together with its lightness and strength, have led to its extensive application to the lighting field, particularly in association with fluorescent tubular lamps. The relatively low softening point (100-110 deg. C.) is something of a limitation for some other applications.

Other acrylic compounds have been applied in the form of dispersions to the coating of paper, in leather finishing, in emulsion paints, and, by cross-linking with other polymers, to form some of the newer synthetic elastomers.

Polyethylene.

Polyethylene or " polythene," available under the trade name " Alkathene," is produced by the polymerisation of the gas ethylene, C_2H_4, at very high pressures. With increasing molecular weight the polymers range from greases—to hard wax-like substances—to white tough leathery materials. The softening point increases with molecular weight.

Just over ten years ago, most of the polyethylene available, because of its special electrical properties, was needed for radar applications. Since then its uses have extended until now it is, perhaps, known to every housewife in the form of a mixing bowl or a bucket, or even as a conduit for the domestic water supply.

In industry too, its applications are many and varied : ducts and drainpipes, flame-sprayed coatings on paper, wood or metal for resistance to corrosion or acid attack ; flexible bottles, containers and extruded films are also available. The material may be welded with a hot nitrogen torch, or, in film form, readily heat sealed.

This material, chemically simple, is an outstanding example of the valuable chance discovery in long term exploratory research that can eventually pay such large dividends. It was discovered in the laboratories of Imperial Chemical Industries in 1933 in the course of a general exploration of the possibilities of chemical reaction at extremely high pressures.

Expanded Plastics.

Expanded plastics, known also as " foamed " or cellular plastics, can be made in a number of ways.

A gas may be dissolved in the soft plastic mass under high pressure. On releasing the pressure, the expanding gas makes the mass porous.

Another method involves the incorporation of a chemical which decomposes on heating, releasing a

gas. The pores in the mass can, if required, be separated from one another and liquids cannot penetrate into these closed pore structures.

These materials are effective heat insulators ; thermal conductivities as low as 0·20-0·35 B.T.U. sq. ft./hr./in./deg. F. can be obtained. The range of cell dimension is approximately 0·004 in.-0·02 in. The specific gravity of the material is usually in the range 0·1-0·3.

Expanded plastics can be made either rigid or flexible according to the type of resin used. The properties may be modified by pigments and fillers. The materials can usually be machined, formed and cut. They may be made as boards ½ in. to 5 in. thick, 2 ft. wide and up to 5 ft. long. Expanded vinyl polymers, polyesters, cellulose acetate and the phenolic, urea and melamine resins are also available and each has a wide field of application, the final choice being based on considerations of economics and of physical and chemical properties.

Closed pore materials have been used for thermal insulation, e.g. in refrigerating equipment.

Cellular polythene, a fairly recent development, is a lightweight material having a number of attractive properties for some electrical applications. The cellular material has lower electrical losses than solid polythene because of the lower dielectric constant : the power factor is essentially the same.

Expanded polystyrene, weighing only 1½-2 lb. per cu. ft., has been used extensively for thermal insulation and also because of its buoyancy, in life belts and rafts.

IRRADIATION OF PLASTICS IN THE ATOMIC PILE.

It was discovered by Charlesby at Harwell in 1952 that when polythene is subjected to high energy radiation, such as is available in the B.E.P.O. atomic pile, cross links are formed between the molecules and the nature of the material is changed. It no longer melts as before at about 115 deg. C. but is transformed into a rubber-like or gel material which does not melt even at 300 deg. C. The process is not unlike that of the vulcanisation of rubber, except that it takes place without the introduction of foreign atoms.

In polythene, crystalline and amorphous phases are present initially in the ratio of approximately 2 to 1. Highly irradiated polythene can lose its crystallinity completely as the degree of internal cross-linking of the molecules takes place.

With some other plastics, for example, " Perspex ", an exactly opposite process of degradation takes place on irradiation.

The industrial possibilities of such a process are by no means properly evaluated : they are certainly not limited to polythene. Obviously, energy of such a high basic cost will have to bring about some very worthwhile effects to justify its use. Experimental work on the irradiation of drying oils from a radioactive cobalt source is already giving very promising results.

The discovery is of the greatest significance and there is already more than a suggestion that it will also be of great value to the radio-biologist in his studies of cell systems.

THE IMPACT OF PLASTICS ON ENGINEERING.

Although the chemical prospect is continuously changing and further new developments in the field of plastics may be just round the corner, a survey of the last ten years would hardly justify the conclusion that we are in the middle of a great technical revolution such as took place in the changeover from wood to metal as a major material of engineering construction. To quote J. E. Gordon of the Royal Aircraft Establishment, " Enormous quantities of wood are used today, perhaps more than metal, certainly more than in 1800. The coming of metals, however, transformed engineering by transforming people's ideas, and perhaps we shall find plastics acting in a similar way as a catalyst for a new Industrial Revolution."

That few revolutionary ideas have been stimulated by the availability of many varieties of existing plastics is perhaps easily understandable. The quantities available are still relatively small compared with metals. It is only recently that the annual output of any one of the plastics has been given in tonnage ; it is more customary to quote figures in terms of multiples of 1,000 lb. Prices, too, are high relative to the commoner metals, and strengths, as understood by the engineer, are low.

But it may be also that the engineer has not yet approached these newer materials in a sufficiently adventurous way ; he has continued to think in terms of fabricating all kinds of structures from sheets and angles and the other shapes that have been made available to him for so long. Revolutionary progress in the use of plastics is not likely to take place along those lines. Nor does the engineer perhaps comprehend as readily as does the chemist the dynamic nature of the chemical revolution that has brought into being these materials with such remarkable properties. The molecules have been truly " tailored " to give materials like Nylon and " Terylene." A study of even the more fortuitously discovered materials can be made to point the way later to the chemical design of new compounds.

The electrical industry was among the very first to make use of plastics and it continues to make increasing use of them where efficiency of shape and function commend them. Often, too, there is a distinct advantage over other materials from the aesthetic point of view. Colour and surface qualities and freedom from corrosion may all play their part in the selection of a plastic rather than wood, metal or glass in any particular case.

In many applications, of course, plastics are used in conjunction with wood or metal or glass. The synthetic glues are used in the bonding of plywood or of the light alloys, particularly in the aircraft industry. Structures essentially composed of plastic may have a wood veneer.

A very attractive range of laminated sheets is available for table tops, bench tops, wall panels, etc.

It is the alliance with glass which promises to give what is perhaps the first real sign of the use of plastics as engineering materials of construction on a fairly large scale. It was mentioned earlier that polyester-glass fibre combinations, for example, have been used as the constructional material of boats and motor-car bodies.

But the man in the street is probably conscious of the more trivial uses of plastics in the domestic field. Even the last two years have seen a large increase in the number of small articles : bowls, bottles, brushes, sponges, moisture-proof bags and wrappings for use in the shops and in the home.

More major applications are likely to be governed by economic considerations, the development of new techniques of shaping and forming, an improvement in mechanical properties, and perhaps new methods of combining, say, steel or aluminium with plastics.

The electrical industry has a good record in utilising the whole range of plastic materials and it is not without significance that the G.E.C. plastic moulding works at Witton is one of the largest in the country.

In addition to materials of construction, the electrical industry is particularly interested in plastics having improved electrical properties, better heat and moisture resistance, and good adhesion to metals and other materials.

In a field where so much has happened in a decade, prophecy is full of uncertainty. The silicones and the fluorocarbons will almost certainly grow in importance. The availability of thin films of good mechanical strength and of high grade electrical quality for use as a dielectric will also be of immense value to the electrical industry.

A new thermosetting, heat stable material having the electrical properties of the best of the thermoplastics would be of great value.

The full effects of the immense growth of our national chemical industry may not be felt for another decade, but they cannot fail in the meantime to influence in some measure design and method in the engineering industries.

TECHNICAL LITERATURE

A digest of recent articles and papers, by members of the G.E.C. and its associated companies

THE LUMINESCENT PROPERTIES AND CRYSTAL STRUCTURE OF SOME NEW PHOSPHOR SYSTEMS (569).*

By A. H. McKeag and E. G. Steward (Research Laboratories).

British Journal of Applied Physics, Luminescence Supplement No. 4, pp. S 26-S 31, 1955.

New phosphor systems are described which illustrate the importance of combining the study of fluorescent properties of new systems with the results of X-ray analysis. The systems described include a range of tin-activated pyro- and tetra-phosphates of strontium and barium, and a group of manganese or cerium-manganese-activated silicates containing lithium. The preparation and fluorescent properties of these phosphors are discussed.

X-ray methods have been used to identify the phases responsible for the various phosphors and a number of new phases including polymorphic forms, have been found. X-ray powder diffraction data are included.

The practical importance of the new phosphors is discussed with reference to fluorescent lamps in general. Emphasis is placed on the colour correction of high-pressure mercury-vapour lamps by certain members of the complex lithium-containing silicate phosphors.

THE RAPID DETERMINATION OF LIME AND MAGNESIA IN SODA-LIME GLASSES (578).*

By H. J. Cluley (Research Laboratories).

The Analyst, Vol. 79, No. 942, pp. 567-573, September, 1954.

The complexometric titration of calcium and magnesium permits the rapid determination of these elements in soda-lime glasses.

After decomposition of the sample with hydrofluoric and perchloric acids, aluminium and iron are removed by extraction with a solution of 8-hydroxyquinoline in chloroform at pH 5; calcium is then determined by titration with disodium ethylene-diaminetetra-acetate, murexide being used as indicator.

On a separate portion of sample treated similarly, the sum of the calcium and magnesium contents is determined by titration with disodium ethylene-diaminetetra-acetate, Eriochrome Black T being used as indicator ; the magnesium content is calculated from the difference between the two titrations.

Determinations on a number of glasses, including a standard sample, show good agreement with results by classical procedures. By the proposed method, duplicate determinations of lime and magnesia in a soda-lime glass can be completed in about 3 hours.

EXPERIMENTAL EQUIPMENT AND TECHNIQUES FOR A STUDY OF MILLIMETRE-WAVE PROPAGATION (582).*

By W. E. Willshaw, H. R. L. Lamont and E. M. Hickin (Research Laboratories).

Proceedings I.E.E., Vol. 102, Part B, No. 1, January, 1955.

Apparatus has been developed to study the characteristics of radio-wave propagation in the region of the oxygen absorption band (wavelengths, 4–6 mm.). The sources of power were crystal harmonic generators and pulse and c.w. magnetrons, and the design of crystal detectors and mixers is des-

cribed. The construction of waveguide components for this wavelength range is discussed, together with equipment for measurement of impedance, frequency, power and attenuation. For most of the propagation measurements, a transmitter with an output of a few microwatts was used, together with a calibrated superheterodyne receiver. Communication tests were carried out with a pulse-frequency-modulated magnetron transmitter.

Measurements of the oxygen attenuation over paths of a few kilometres have been made at a number of wavelengths in the absorption band. Measurements over sea have given values of the reflection coefficient of the sea surface. These results are summarised and discussed briefly.

NOISE IN CUT-OFF MAGNETRONS (585).*

By R. C. Glass, G. D. Sims, and A. G. Stainsby (Research Laboratories).

Proceedings I.E.E., Vol. 102, *Part B, No.* 1, *January*, 1955.

Experiments have been made on the characteristics of magnetron oscillators at anode voltages from zero to the value at which the oscillations start. In particular, the noise in the anode current was investigated. Discrete peaks of noise were found in the spectrum, and the frequency at which they occurred varied in a regular manner with anode voltage and magnetic field strength. A qualitative explanation of these peaks is given, and the implication of these results on the mechanism of build-up of oscillations and the selection of modes of oscillation is discussed.

ATOMIC CONFIGURATIONS IN LUMINESCENT CENTRES (566).*

By W. A. Runciman (Research Laboratories.)

British Journal of Applied Physics, Luminescence Supplement No. 4, *pp. S* 78-*S* 85, 1955.

When the activator ions in a phosphor have a charge different from that of any ions in the host lattice, it is generally agreed that charge compensation must take place. A new theory of luminescent centres is proposed in which the compensation of charge, by lattice vacancies or by activator ions, is localised in the vicinity of the activator ions. This theory is primarily applicable to ionic crystals, and specific configurations of lowest energy can be deduced. These configurations are described in detail for alkaline-earth oxide, uranate and fluoride phosphors. and the vibrations of these centres are discussed. A number of original phosphors of theoretical interest, including CaO . Bi, Li ; CaO . U, Li ; CaO . U, Sm ; and the uranates, is described and spectra are shown. Finally, necessary modifications of the present theories of sensitised luminescence and multiple-band emission are considered.

THE INTERPRETATION OF HALL EFFECT, CONDUCTIVITY AND INFRA-RED MEASUREMENTS IN INDIUM ANTIMONIDE (600).*

By I. G. Austin and D. R. McClymont (Research Laboratories).

Physica, Vol. 20, *No.* 11, *pp.* 1077-1083, *November*, 1954.

The Hall effect, conductivity and infra-red transmission characteristics of indium antimonide have been measured over a temperature range. It is shown that a direct determination of energy gap from Hall or conductivity data is not possible, since intrinsic conditions are barely obtained By taking a measured value for the variation of optical gap with temperature it is possible to deduce a value for $M^* = \sqrt{m_e m_h}/m$ and the energy gap at room temperature. The conclusions are in substantial agreement with those of previous workers based on slightly different assumptions.

HEAT TRANSFER THROUGH OXIDE-CATHODE MATERIALS (589).*

By A. E. Pengelly (Research Laboratories).

British Journal of Applied Physics. Vol. 6, *pp.* 18-20, *January* 1955.

A method of measuring the thermal conductivity and opacity of poorly conducting translucent materials has been developed and used to measure the conductivities at about 150 deg. C. of poly-crystalline barium oxide, strontium oxide and an equimolecular mixture of the two with and without $2\frac{1}{2}$ per cent. zirconium oxide or 5 per cent. zirconium added. These oxides were in the form used for typical oxide-cathode coating. The sum of the absorption and scattering coefficients has in each case been estimated from the results.

THERMAL ACCEPTORS IN GERMANIUM (604).*

By R. J. Hodgkinson (Research Laboratories).

Physica, Vol. 20, *No.* 11, *pp.* 1001-1005, *November*, 1954.

It has been suggested that thermal acceptors in germanium are copper atoms, and that the equilibrium thermal acceptor concentration at any temperature is the same as the saturation concentration of copper in solid solution at that temperature. Thurmond and Struthers have already given a thermodynamic treatment of the problem. Although the present approach gives similar results, it enables a clearer physical picture to be given of the processes involved, and the general shape of the solubility curve to be predicted.

NEW SEMICONDUCTING COMPOUNDS OF DIAMOND TYPE STRUCTURE (605).*

By C. H. L. Goodman and R. W. Douglas (Research Laboratories).

Physica, Vol. 20, *No.* 11, *pp.* 1107-1109, *November*, 1954.

This paper discusses new ternary chalcopyrite compounds which closely resemble the binary zinc blende compounds. Two of the new compounds $CuInSe_2$ and $AgInSe_2$ seem of considerable promise in crystal valve applications. High back voltage rectifying characteristics have been obtained with turnovers in excess of 150 volts. Hall effect measurements on a poly-crystalline $CuInSe_2$ specimen of $\approx 0{\cdot}1$ ohm cm resistivity have indicated an electronic mobility of ≈ 300 $cm^2v^{-1}sec^{-1}$. An optical energy gap of $\sim 0{\cdot}9$ eV has been found. It is believed that a substantially higher value of mobility will be obtained with pure single crystal material. Attempts have been made to pull single crystals of $CuInTe_2$, but results have so far not been successful.

MAGNETIC MATERIALS IN THE ELECTRICAL INDUSTRY.

By P. R. Bardell (Research Laboratories).

Macdonald & Co. (Publishers) Ltd., 1955. *Price* 32s. 6d.

This book is intended to be helpful to senior students in physics and electrical engineering, and to physicists and engineers in industry.

Until quite recently the development and production of magnetic materials was largely a matter of chance, the principles underlying their properties being imperfectly understood. An attempt is made to give an understanding of the properties of the large number of magnetic materials now available, as the subject is inherently somewhat difficult and is further obscured by the proprietary names of the commercially available materials.

A glossary of terms and units is included, also tables giving the properties of materials and a note explaining magnetic terminology and units.

Following a discussion of the influence of magnetic theory on the development of materials, an account is given of the historical development, application and testing of permanent magnets and of soft magnetic materials. Special devices such as sound recorders, non-destructive testers, transductors and transducers are also dealt with. The chapters have been arranged so that each may be read as a separate entity.

THE PERFORMANCE OF ELECTRICAL AIRBREAK CONTACTS.

By H. F. Jones (Witton Laboratories).

The Engineer, Vol. 178, *No.* 4639, *pp.* 826-827, *December 24th*, 1954.

The essential requirements of contact materials are outlined, together with the rates of wear of typical industrial contactors with a wide variety of contact materials. The various factors influencing contact life are discussed.

THE SCIENTIFIC TESTING OF DOMESTIC APPLIANCES.

By L. S. Moore (Witton Laboratories).

Electrical and Radio Trading, pp. 41-42, *November 20th*, 1954.

Types of laboratory tests necessary to develop original designs of motorised domestic appliances. Also the part the laboratory plays in maintaining quality of production.

CONTRIBUTIONS TO THE STUDY OF RECTIFIER AND NETWORK HARMONICS AND THEIR EVALUATION FOR TRACING THE SOURCES OF WAVE DISTORTIONS.

By E. Friedlander (Consulting Engineer, Witton Works) and W. G. Thompson (Witton Laboratories).

C.I.G.R.E. Paper, No. 312, *May*, 1954.

The paper deals with the interaction between harmonics on the A.C. and D.C. side of a rectifier. It is found that the A.C. harmonics penetrate to the D.C. with equal percentage amplitudes, whereas the predominant D.C. current ripples are transferred to the A.C. side and are shared by the associated pairs of A.C. harmonics in each of the three phases. The second part of the paper shows a method for discriminating between harmonics of different origin and the discrimination between two sources of harmonics from a single pair of voltage and current oscillograms.

THE ROLE OF A LABORATORY IN SERVING A LARGE WORKS.

By W. G. Thompson (Witton Laboratories).

" *The Manager*," *Vol.* 23, *No.* 4, *p.* 277. *April*, 1955.

Owing to the complexity of modern production methods and exacting standards of performance, a laboratory is an indispensable adjunct to a large manufacturing concern. The policy in dealing with routine work, development problems and special investigations is discussed and an indication given of arrangements and methods of control to implement the policy.

PRODUCTIVITY AND METHODS IN MOULDING.

By A. L. Sparshott (Witton Moulded Insulation Works).

Plastics Progress, 1955. (*In Preparation* (*Iliffe & Sons, Ltd.*)).

The paper, which was presented to the British Plastics Exhibition and Convention at Olympia, London, on July 6th, discusses the origin of the term productivity in the sense in which it is now known. Various indices which can be used in connection with the measurement of productivity are examined with particular reference to their use in assessing moulding shop output.

Some factors influencing productivity in compression and transfer injection moulding of thermosetting materials are outlined, including reference to the design of mouldings. Typical press procedures are analysed for common causes of low productivity. Injection moulding of thermo-plastic materials is then considered along similar lines. Finally, the relationship between high productivity and quality is discussed.

THE APPLICATION OF LIFTS FOR OFFICE BUILDINGS.

By A. W. Dixie (The Express Lift Co. Ltd.).

Architectural Design, Vol. 25, *No.* 3, *pp.* 99-102, *March*, 1955.

The author presents a simple and direct method of calculating the lift capacity required for an office block, which can be used by architects during the early stages of planning provided certain assumptions are accepted. His discussion of installation requirements is illustrated with diagrams, and in addition to dealing with lift wells and the location and layout of machine rooms, covers the design of architraves and lobbies to promote smooth flow of traffic. He describes the scope of automatic lift control systems, and concludes by showing how standardisation of technical features can reduce costs while still leaving the architect the opportunity of imparting individuality to the building in features such as car interiors, doors and architraves.

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